Dynamics of volcano-hydrothermal systems

Shaul Hurwitz - USGS – Menlo Park

Hydrothermal explosion in Biscuit Basin, Yellowstone NP - May 17, 2009

Photo: Wade Johnson, UNAVCO

Why study hydrothermal systems?

Hazards

- Hydrothermal explosions
- Water saturated, hydrothermally altered rocks increase the potential for catastrophic sector collapses and destructive lahars
- Source of toxic gases and dissolved metals

Poas Crater Lake,
Costa Rica
25 February 2014

Photo: Smithsonian GVP

Why study hydrothermal systems?

Resources

- Geothermal energy
- Mineral deposits

The Geysers geothermal field with a production of ~ 1 GW

Bingham Canyon Mine, Utah

Produced >19 million tons of copper, more than any other mine

Why study hydrothermal systems?

Life at High Temperatures

Thomas D. Brock[1]

+ See all authors and affiliations

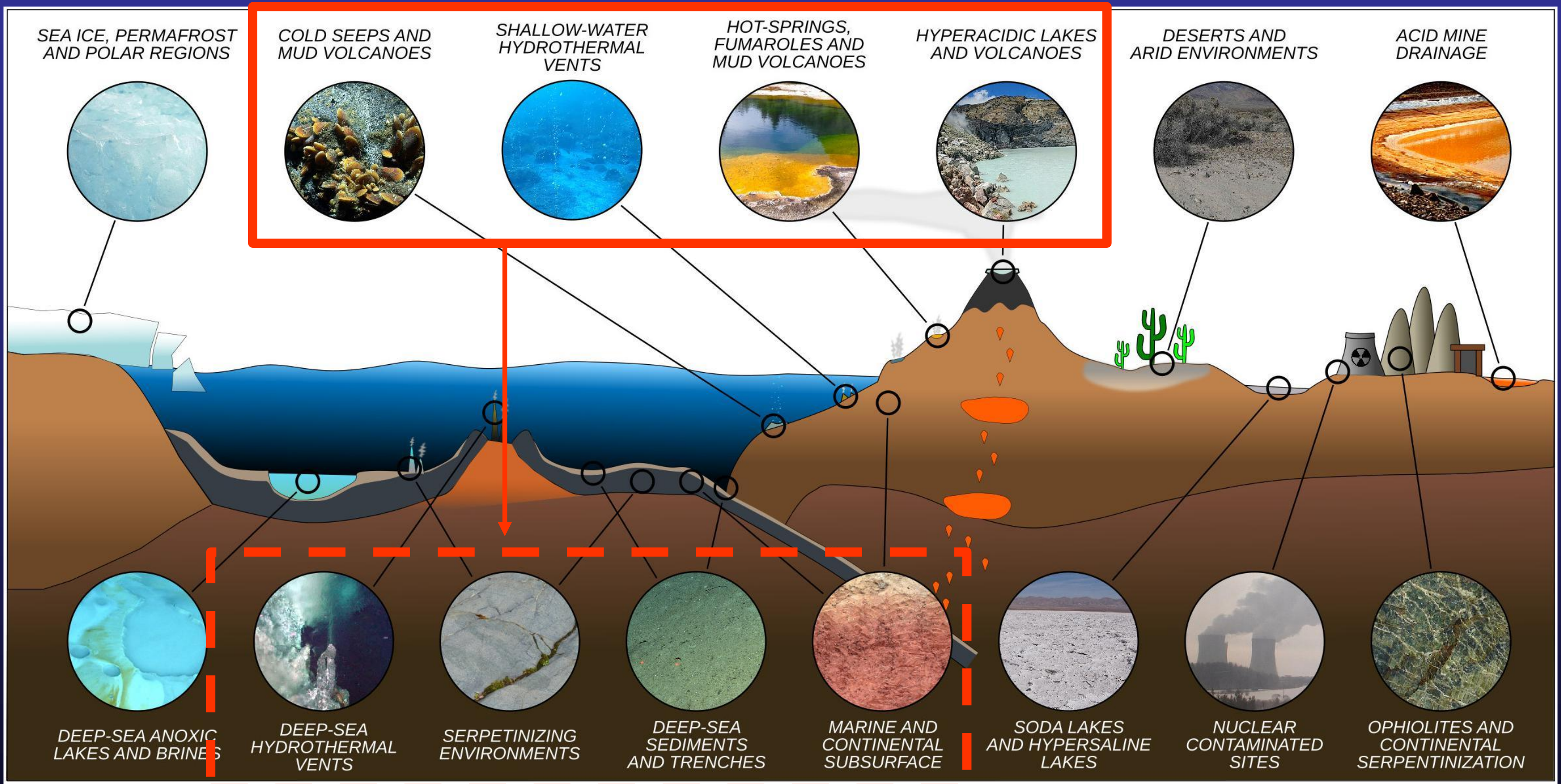
Science 24 Nov 1967:
Vol. 158, Issue 3804, pp. 1012-1019
DOI: 10.1126/science.158.3804.1012

Mushroom Pool, Yellowstone

- The thermophile bacteria ***Thermus aquaticus*** isolated in Yellowstone led to the invention of **PCR** (polymerase chain reaction) that utilizes its heat-resistant enzyme to speed up DNA replication
- This discovery helped create the field of biotechnology and the **onset of the pharmaceutical industry**

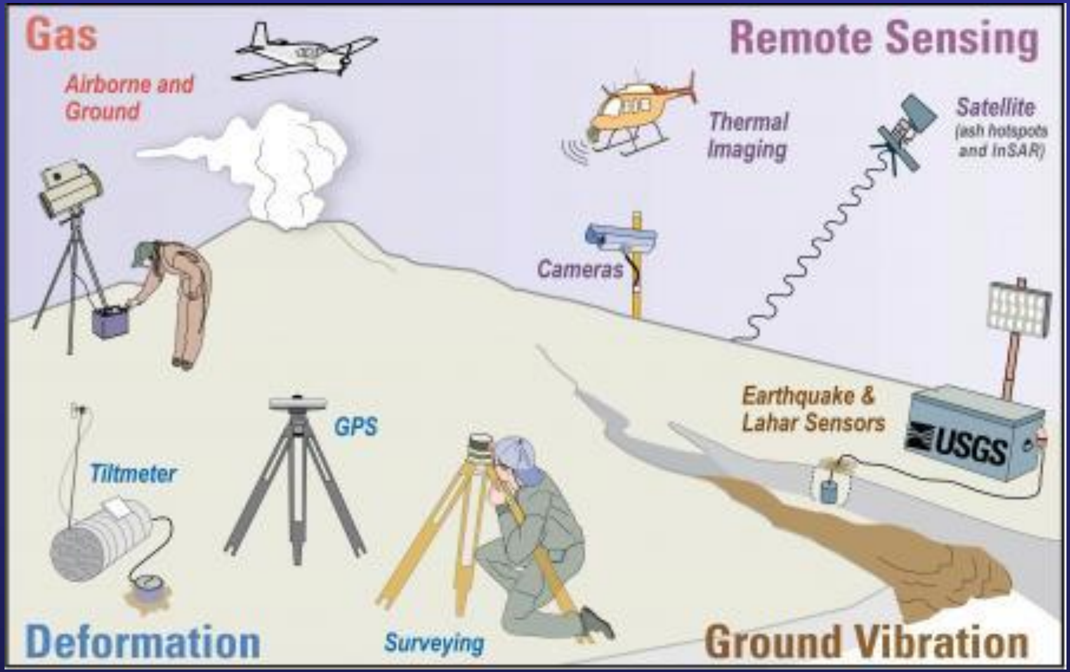
Why study hydrothermal systems?

Analogs for extraterrestrial life



Merino et al. Frontiers in MicroBio 2019

Do signals measured at the surface have magmatic or hydrothermal origins?



Many seismic, geodetic and geochemical signals have **hydrothermal origins,** or have magmatic origins that are **modulated** by the hydrothermal system

Opinion piece

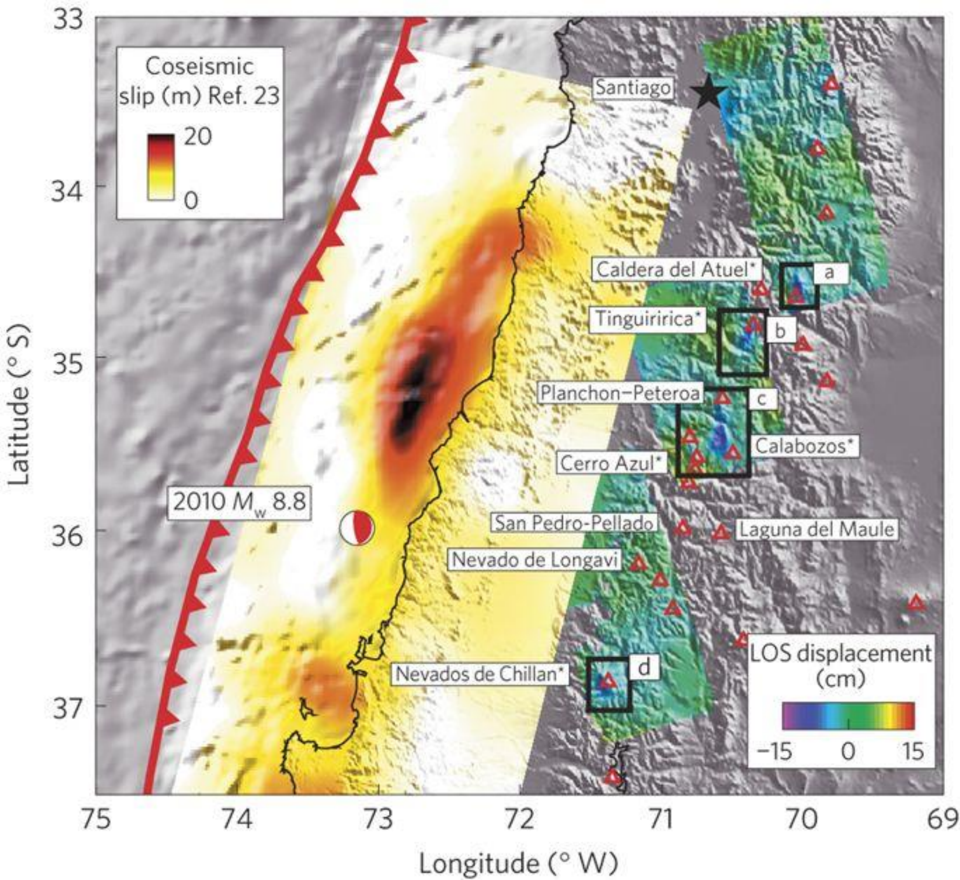
Phil. Transac. Royal Society

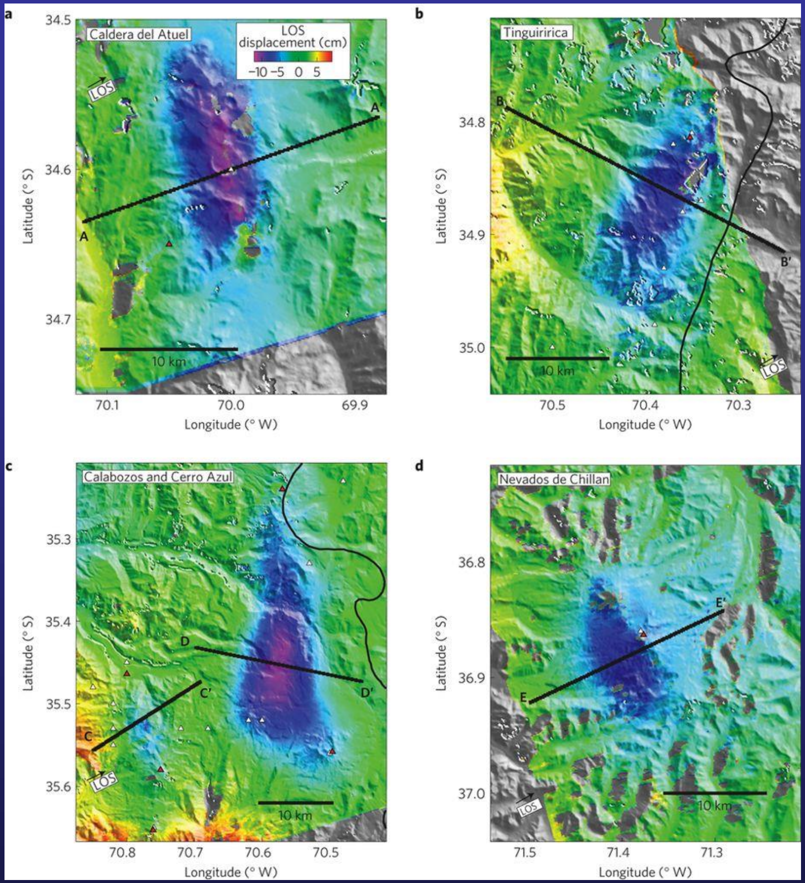
Thoughts on the criteria to determine the origin of volcanic unrest as magmatic or non-magmatic

M. E. Pritchard, T. A. Mather, S. R. McNutt, F. J. Delgado and K. Reath

Published: **07 January 2019** | https://doi.org/10.1098/rsta.2018.0008

2010 M_w 8.8 Maule, Chile earthquake



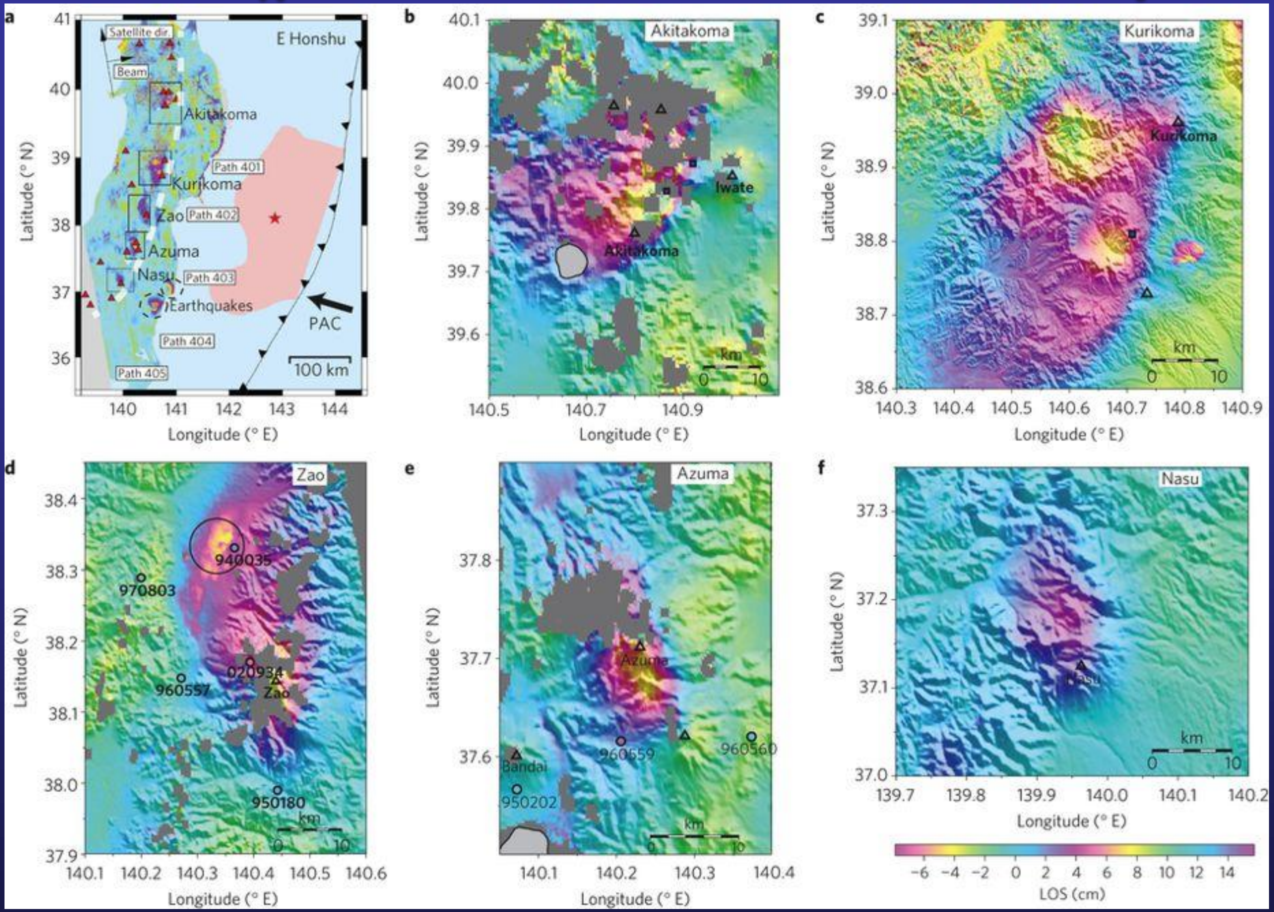


Subsidence of <15 cm in five volcanic areas within weeks

"We suggest that the deformation is related to coseismic release of fluids from hydrothermal systems documented at three of the five subsiding regions"

Pritchard et al., NatureGeo 2033

2011 M_w 9.0 Tohoku earthquake



Volcanic regions 150-200 km from the rupture subsided by <15 cm

“***<u>hot plutonic bodies</u> beneath the volcanoes, that may have deformed and subsided in response to stress changes***”

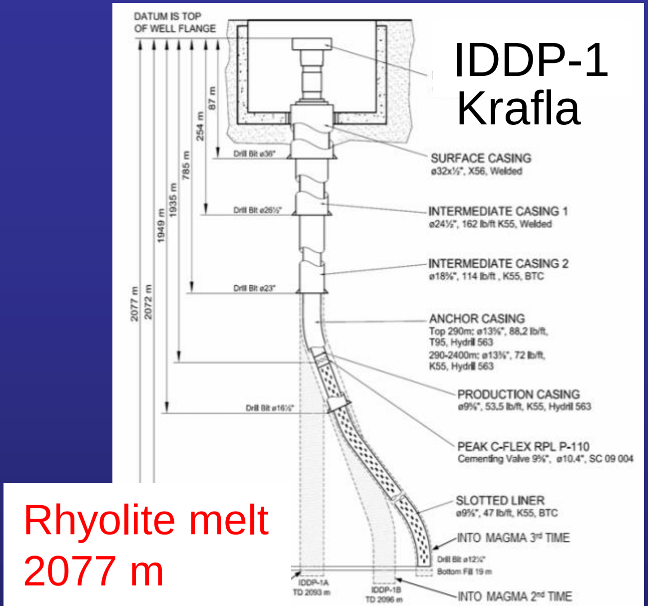
Takada & Fukushima, NatureGeo 2013

Topics to be covered

- Define hydrothermal systems and their relation to the underlying magma
- Empirical methods used to investigate hydrothermal systems
- Properties rocks and multiphase fluids
- Heat and mas transport from magma to the surface
- Available numerical simulators and an example of an application

Observations used in studies of continental hydrothermal systems

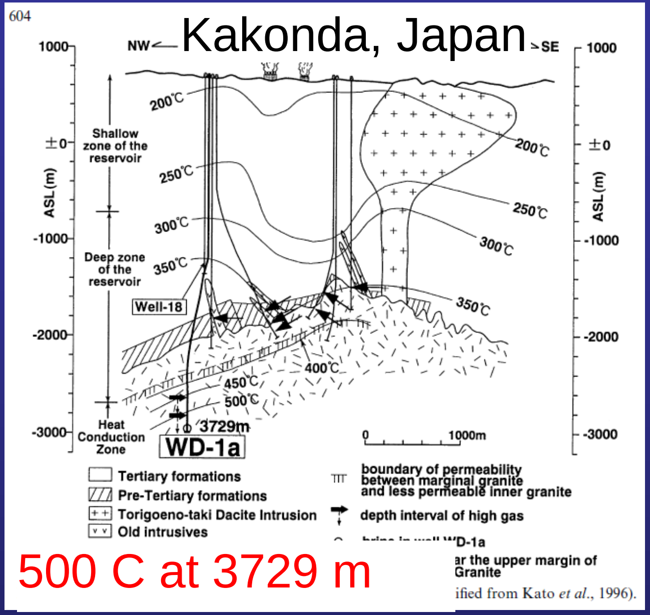
Deep drilling in volcanic areas



IDDP-1
Krafla

Rhyolite melt
2077 m

Friðleifsson et al., 2015



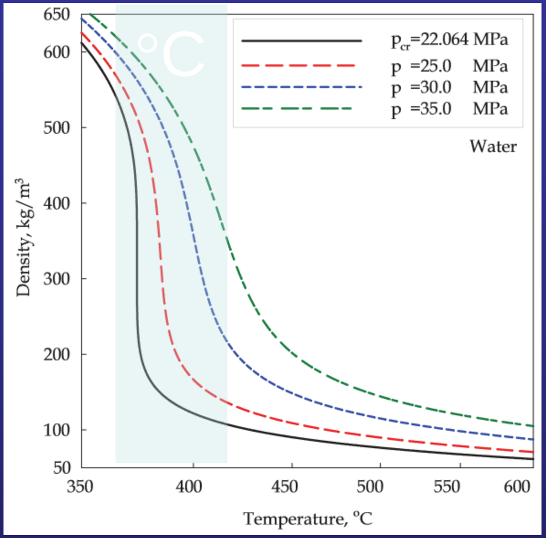
Kakonda, Japan

500 C at 3729 m

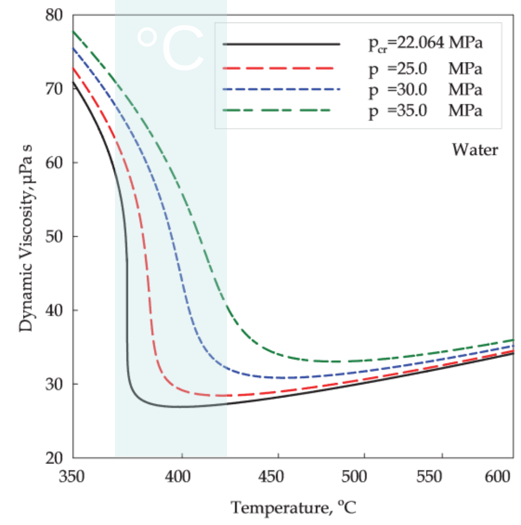
Ikeuchi et al., 1998

- Pre-drilling geophysics was found to be mostly incorrect, but **much was learned about hydrothermal dynamics**
- In deep and hot wells (T< 450 °C) a **narrow zone of low-permeability rocks** formed by mineral deposition
- Above the layer - **brittle rocks and hydrostatic to sub-lithostatic pressures**. Below - **ductile rocks and lithostatic pressures**

Motivation for deep drilling – supercritical geothermal resources



Critical point
374 °C
22.1 MPa



- Very high enthalpy supercritical geothermal systems near the brittle–ductile transition zone can possibly make deep wells economic
- Density and dynamic viscosity undergo a significant drop within a very narrow temperature range, while specific enthalpy sharply increases
- More than 25 deep wells worldwide have encountered temperatures in excess of the critical point

Ongoing and future drilling – supercritical fluids for energy production

Japan Beyond-Brittle Project

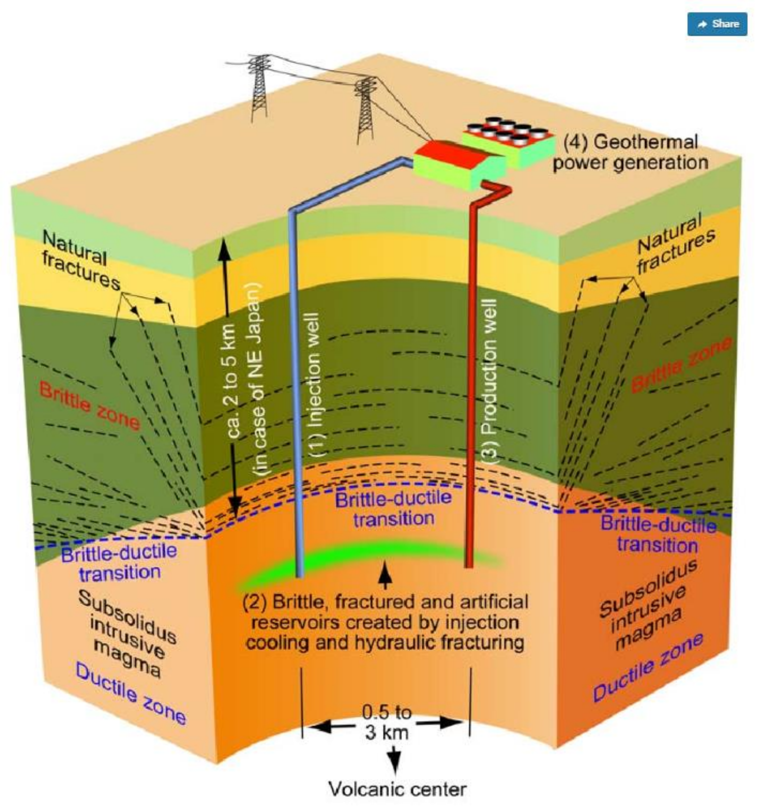
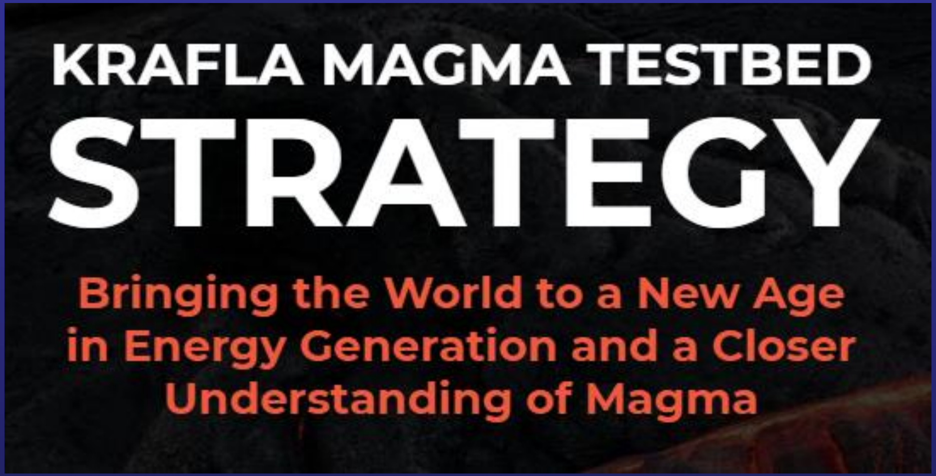


Figure 1. Concept of the EGS reservoir in the ductile zone.



KRAFLA MAGMA TESTBED

STRATEGY

Bringing the World to a New Age in Energy Generation and a Closer Understanding of Magma

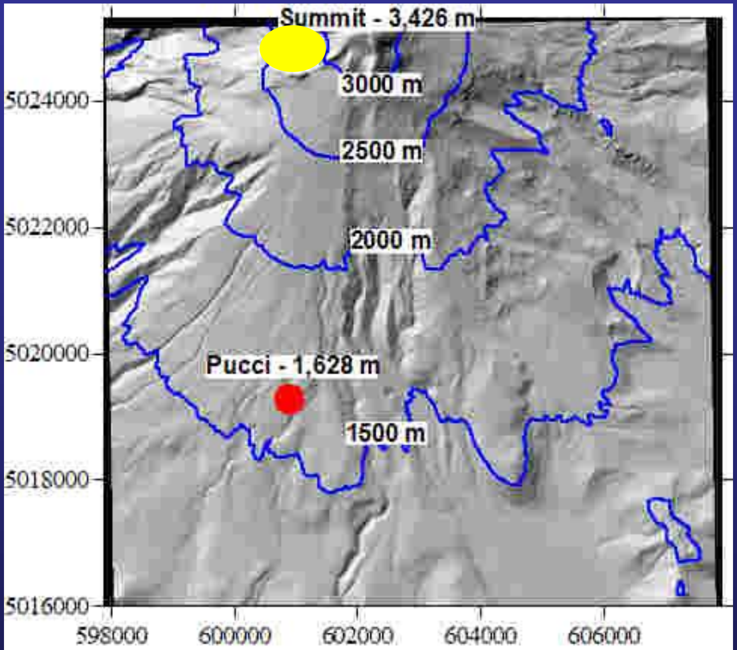
Planning an International Magma Observatory

A planned project will drill into a magma reservoir in Iceland that has never erupted to the surface, giving scientists a fresh look at Earth's underground "plumbing."

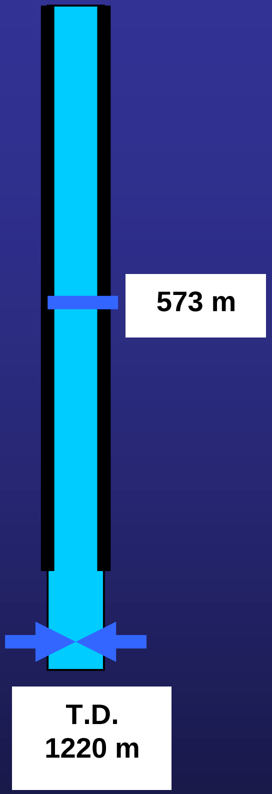
By John Eichelberger 25 June 2019

Drilling in steep stratovolcanoes -how much water is in a volcanic edifice?

Pucci Well at Mt. Hood



Near Timberline Lodge

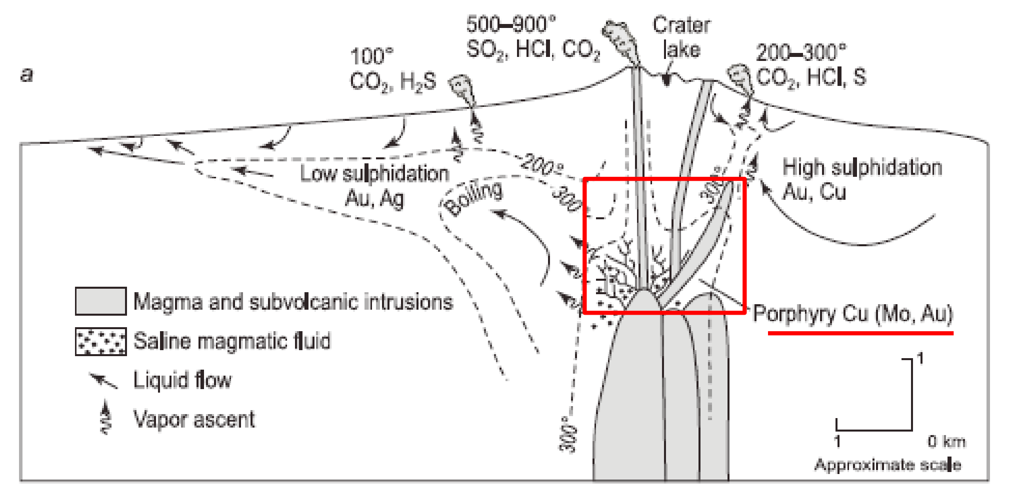

573 m

T.D.
1220 m

- Drilled ~ 1600 below the summit
- Deep water table ~ 573 m
- Near summit vent at boiling temperature with magmatic gases suggests (high ^{3}He/^{4}He) a dry conduit
- **“Dry” core and wet lower outer flanks**

Ore deposits – windows into ancient hydrothermal systems

Chuquicamata, Chile



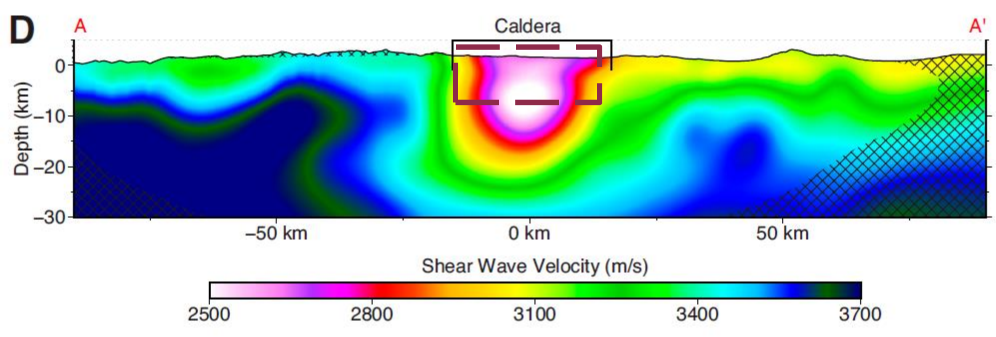
Hedenquist and Lowenstern (Nature 1994)

- Voluminous porphyry ore deposits have economic amounts of copper and often molybdenum, silver and gold
- **Magmatic vapors and hypersaline liquids** are a **primary source of metals** in ore deposits
- Metals are also **leached from rocks** enhanced by acid magmatic vapors absorbed by meteoric waters

Inferences from geophysics

Seismic tomography

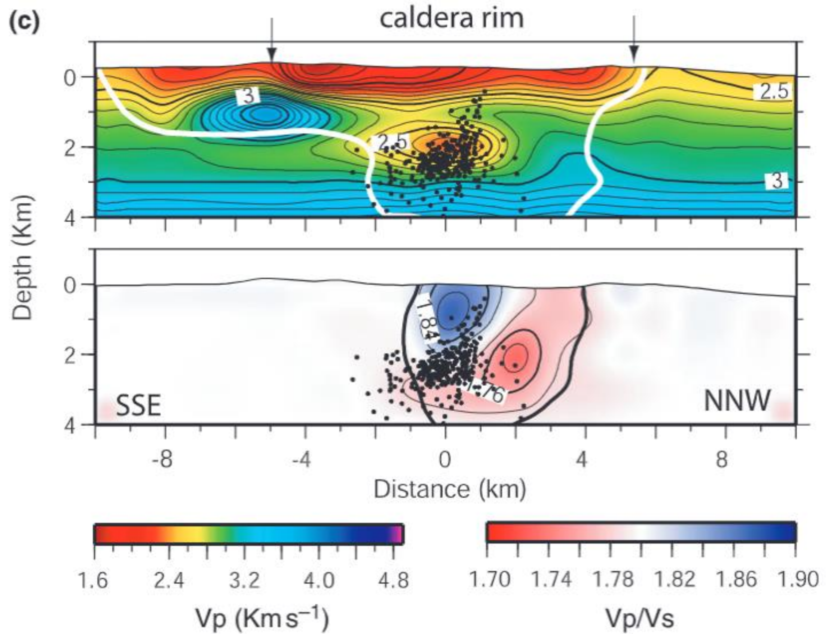
Long Valley caldera



Flinders et al., Geology 2018

- Not enough resolution to detect spatial variations in the shallow crust

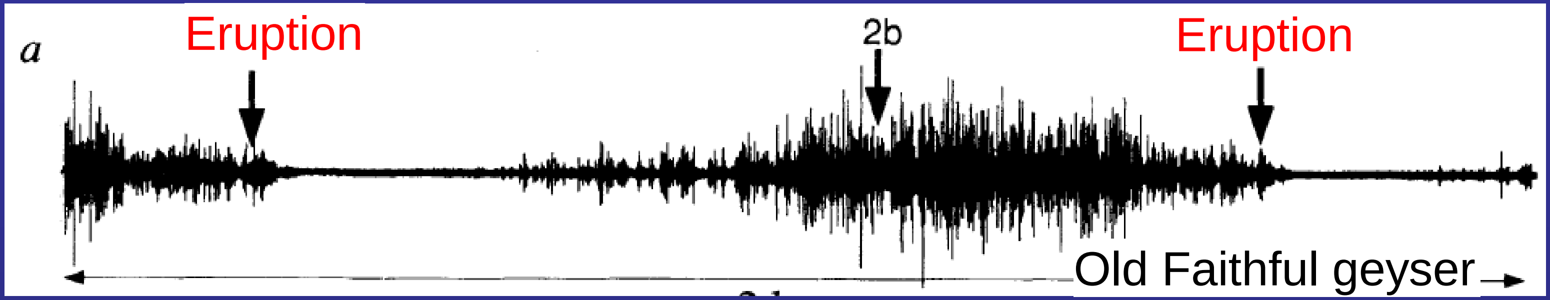
Campi Flegrei caldera



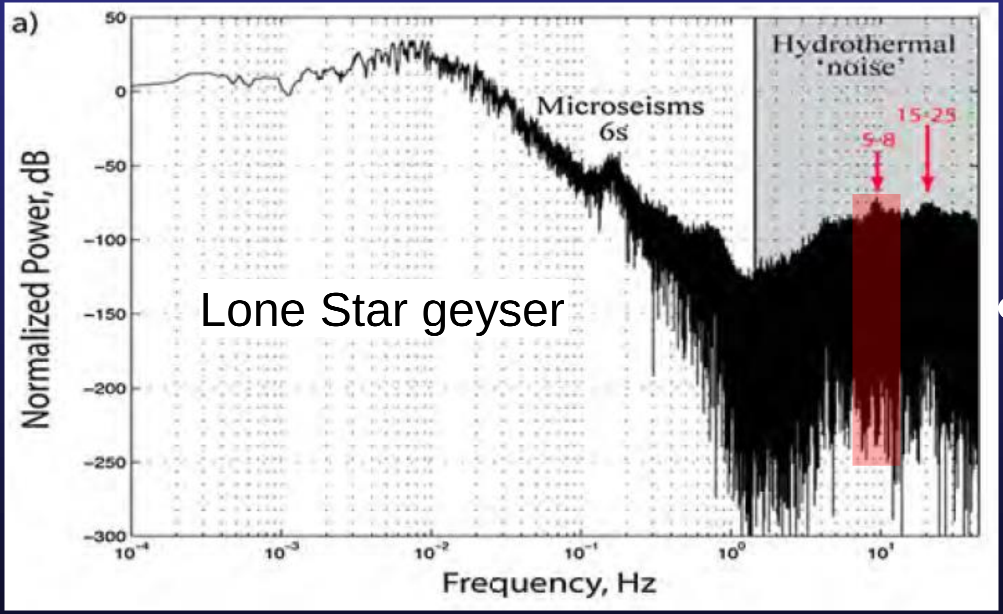
Chiarabba & Moretti, 2006

- P wave to S-wave velocity ratio **(Vp/Vs)** tomography is useful for delineating structures of, and within hydrothermal systems

Broadband seismometers at geysers



Kedar et al., Nature 1996

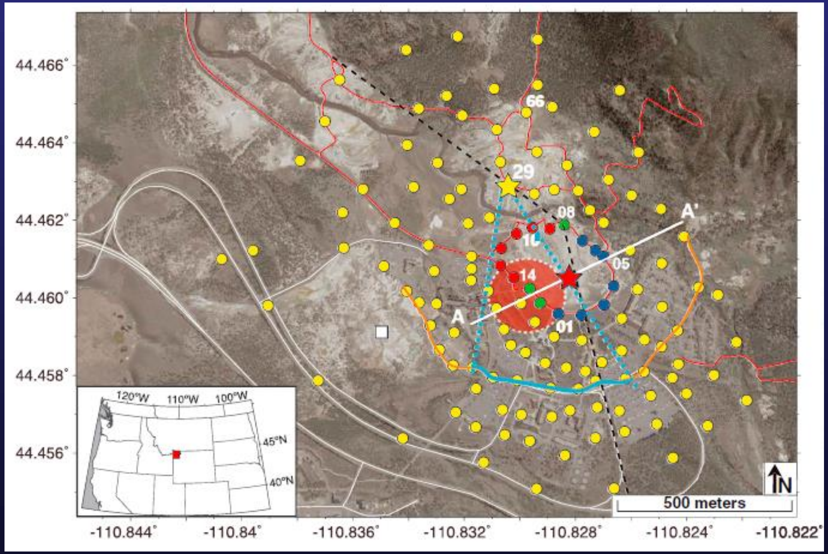


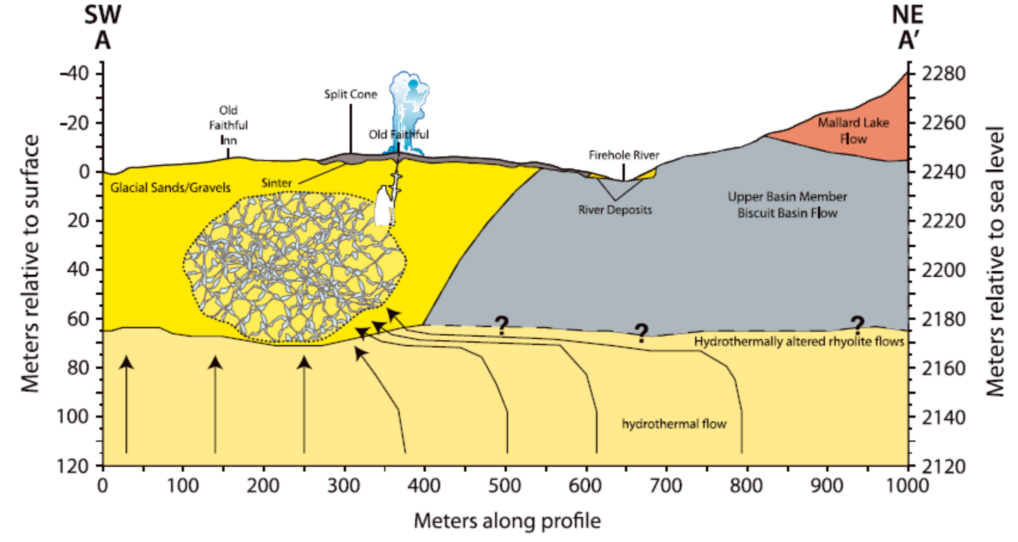
Vandemeulebrouck et al., JGR 2014

- Broadband seismometers record multiphase processes leading to an eruption at multiple frequencies
- The frequency of hydrothermal tremor generated by impulsive pressure signals associated with bubble collapse is mainly ~ 1–10 Hz band

Nodal seismometers at Old Faithful

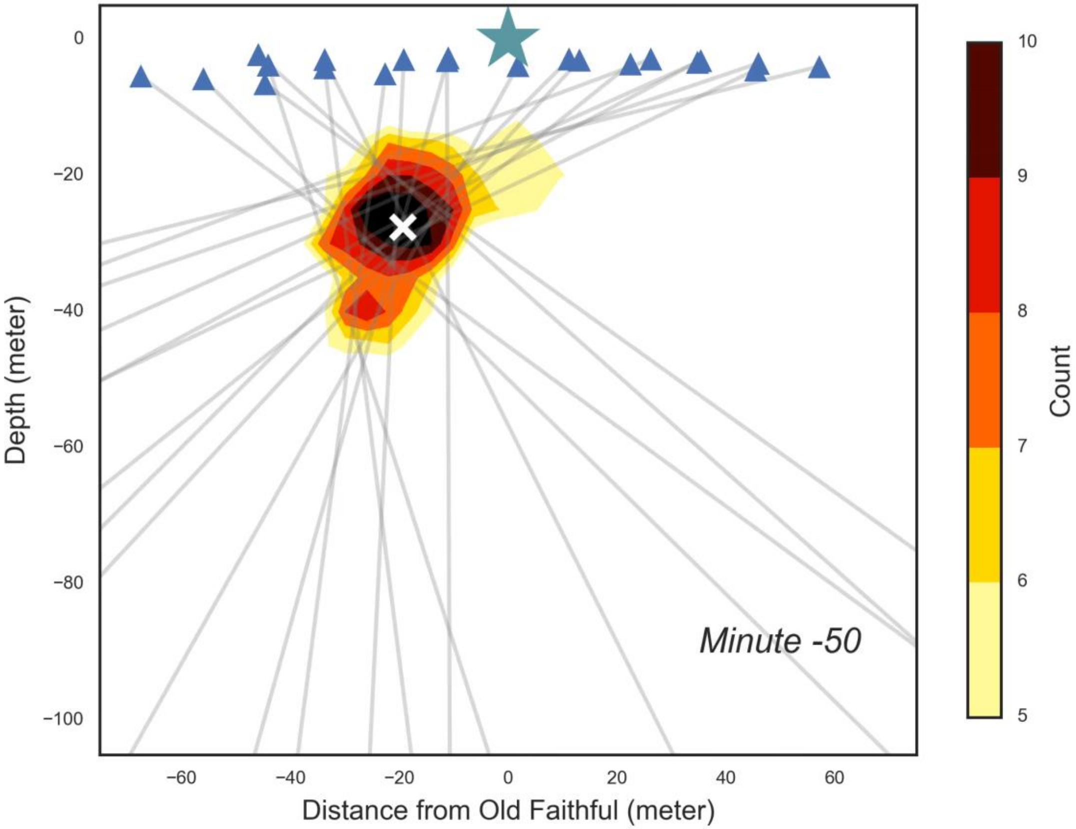
- Dense arrays of nodal geophones can track the 3-D migration of hydrothermal tremor throughout the eruption cycle
- Delineating subsurface reservoirs and their dimensions depends on array density and configuration





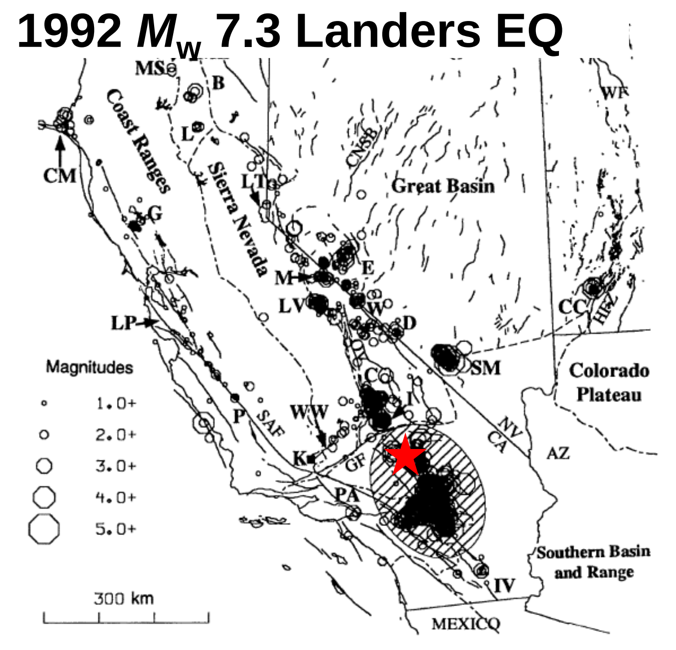
Wu et al., GRL 2017

Hydrothermal tremor migration at Old Faithful geyser



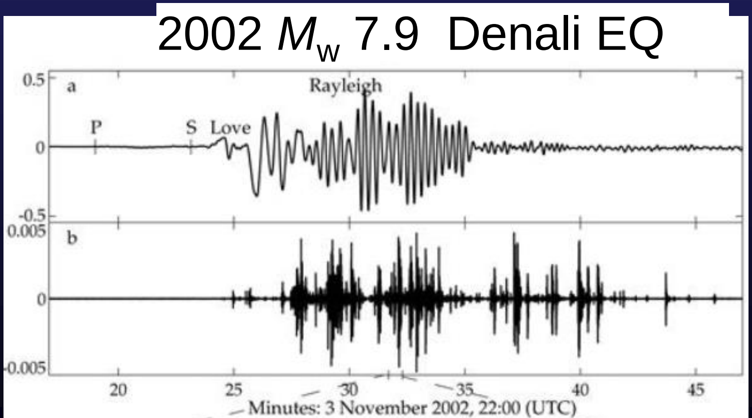
Wu et al JGRL in press

Preferential earthquake triggering in hydrothermal systems



1992 M_w 7.3 Landers EQ

Hill et al., Science 1993

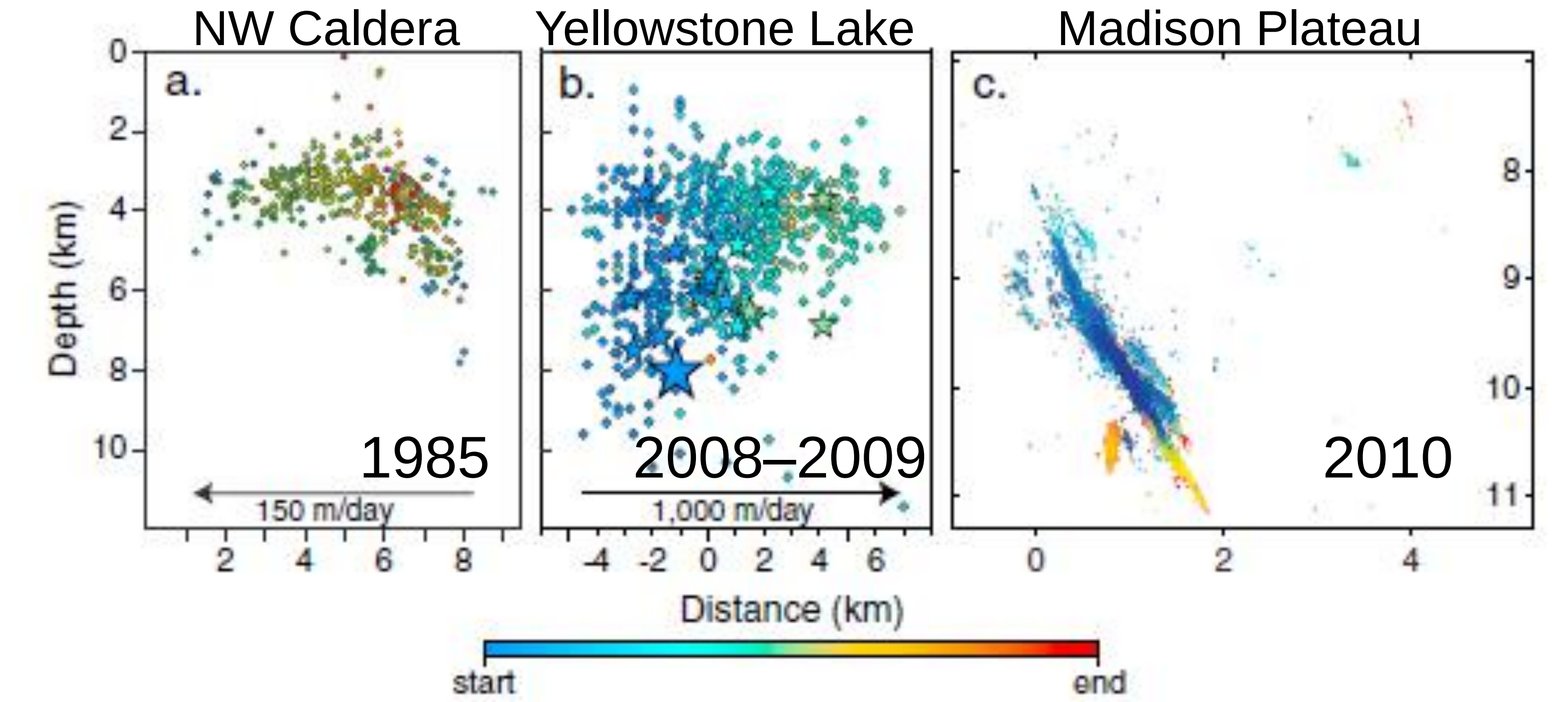


2002 M_w 7.9 Denali EQ

Prejean et al., BSSA 2004

- Seismic swarms (<6 km depth) are **preferentially triggered in hydrothermal areas**
- **Love & Rayleigh waves (15-40 sec) trigger** the swarms ($M \le 2.5$)
- The small dynamic stresses (<10 kPa) suggest a **critically stressed crust in hydrothermal areas** of the Western US

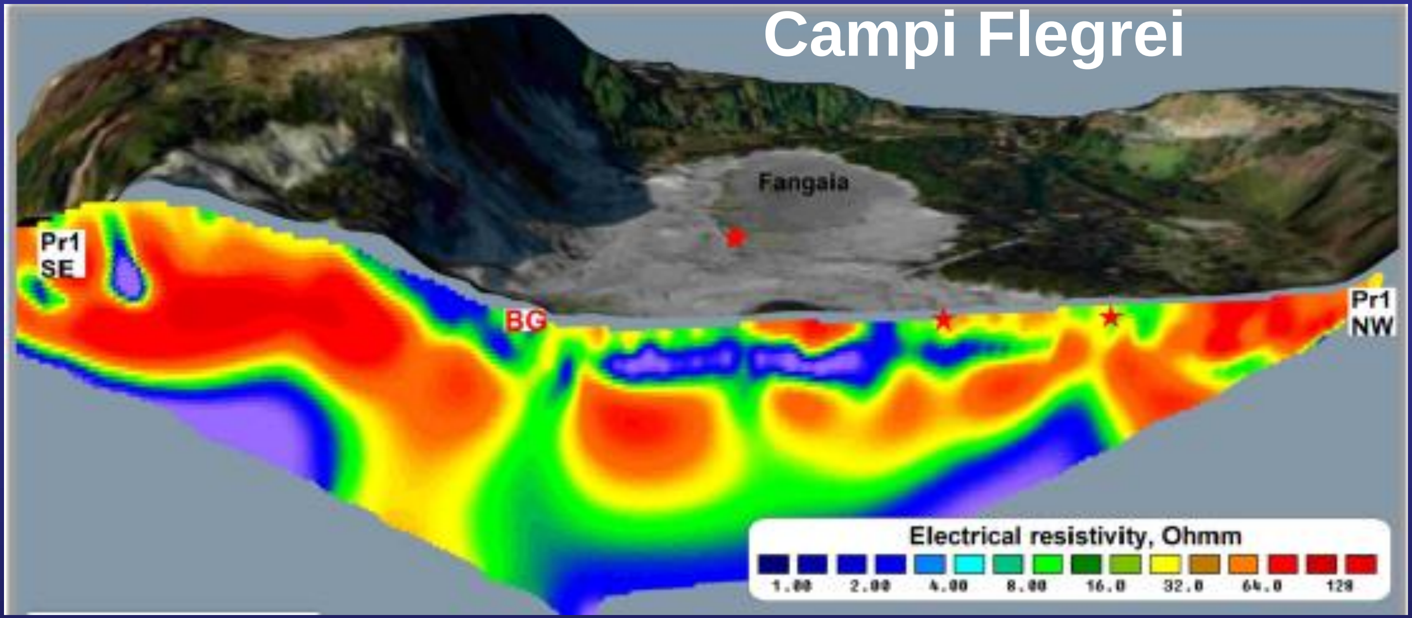
Spatial and temporal patterns of seismic swarms in Yellowstone



Waite & Smith, 2004 Farrell et al., 2014 Shelly et al., 2014

Earthquake swarms in the upper crust
have defined spatial and temporal patterns

Electric, electromagnetic, magnetic methods

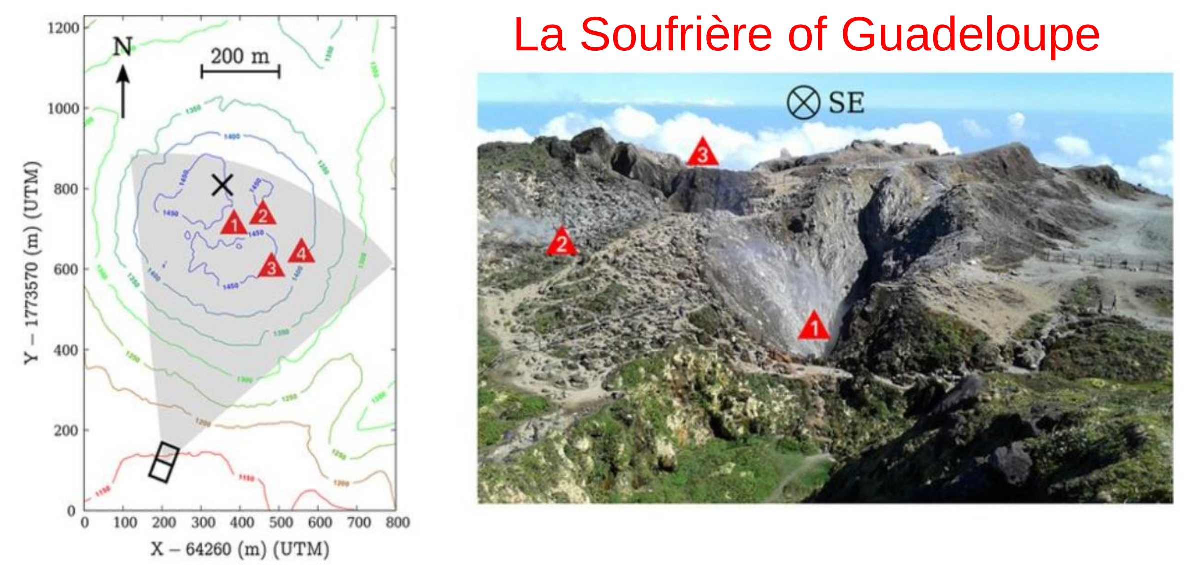


Byrdina et al., JVGR2014

- Hydrothermal alteration reduces the electrical resistivity and magnetization of volcanic rock
- Large contrasts between electrically conductive thermal fluids and clay minerals and the surrounding (colder and/or unaltered) resistive host rocks
- Very few continuous measurements in volcanic systems

Cosmic-ray muon radiography

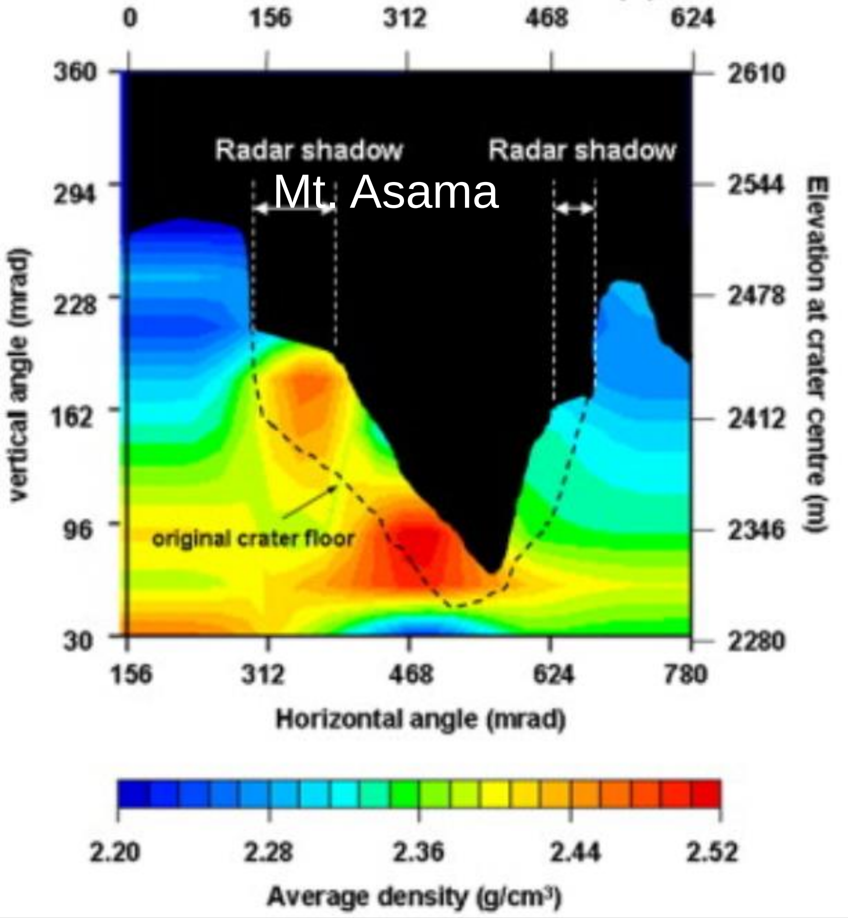
- Cosmic-ray muons generated in the atmosphere continuously bombard the Earth's surface from above, arriving at all angles
- Cosmic-ray muon radiography can be applied by placing a detector to image density variations in a volume that is higher in elevation


La Soufrière of Guadeloupe

▲ active zones visible at the dome surface

Jourde et al. SciRep 2016

Cosmic-ray muon radiography

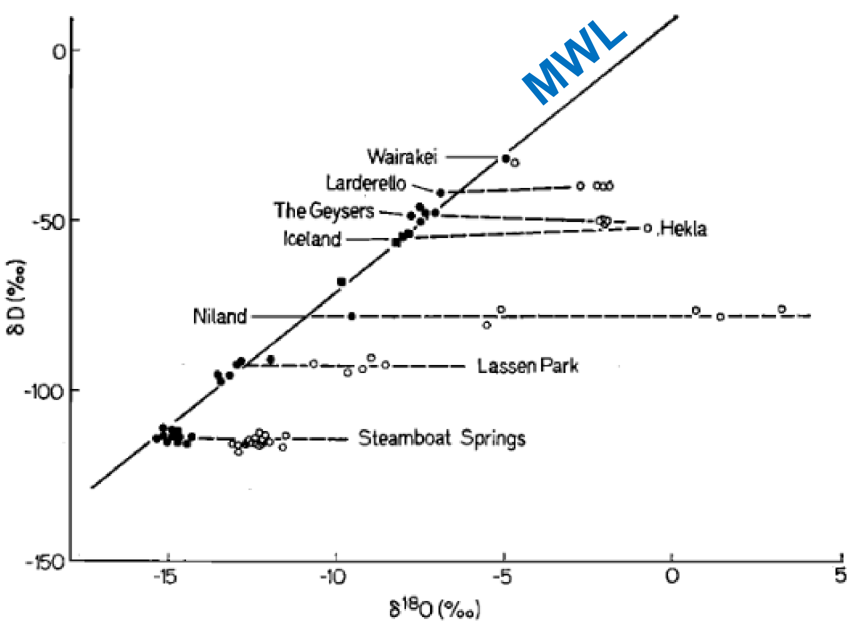


- **3-D density variations that** can result from the heterogeneous distribution of lithology or water saturation
- Less useful in calderas and shield volcanoes

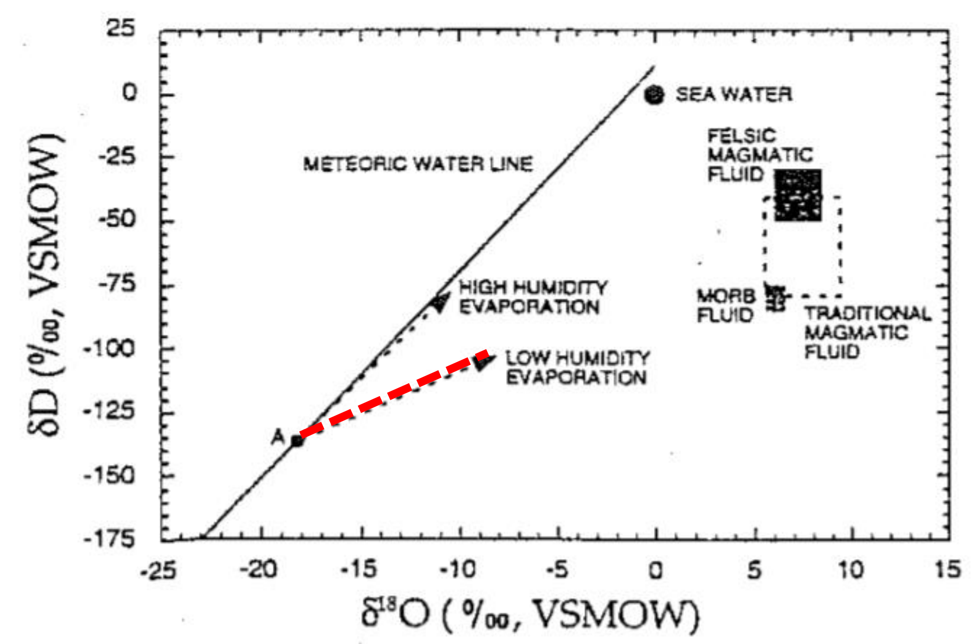
Tanaka et al. EPSL 2007

Inferences from the chemical and isotopic composition of thermal waters and gas

Origin of water in hydrothermal systems



Taylor, Econ. Geol. 1974

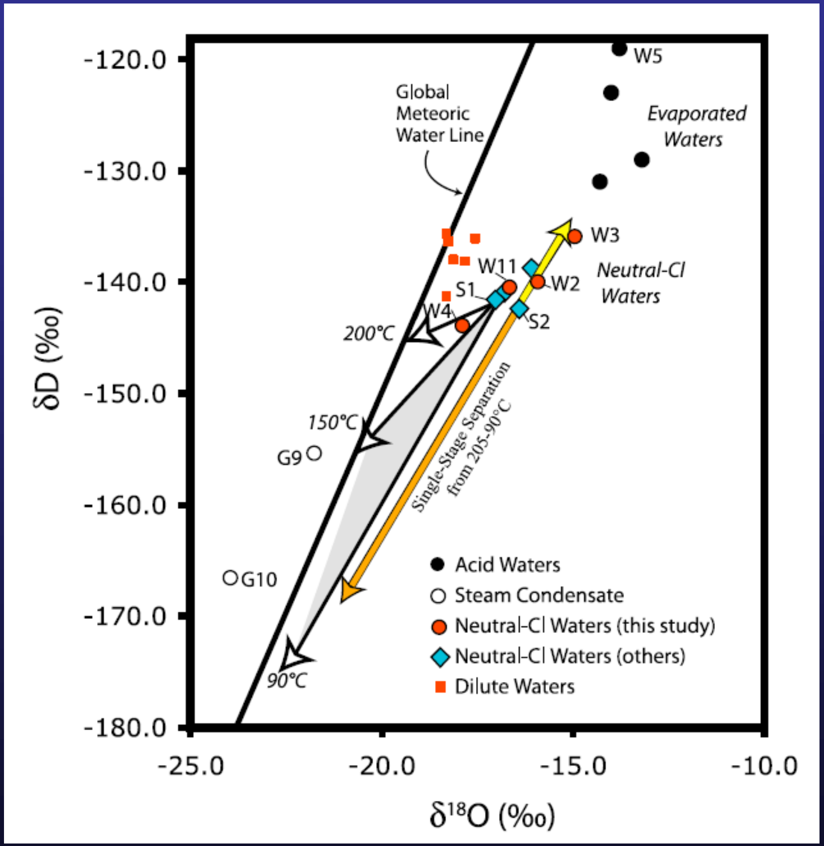


Campbell & Larson, Rev. Econ. Geol. 1998

- The isotopic composition of all waters discharged from volcanic systems can be traced to **meteoric water recharge**
- The amounts of magma-derived water in volcano-hydrothermal systems is negligible
- In multiphase systems, boiling and evaporation change the composition significantly

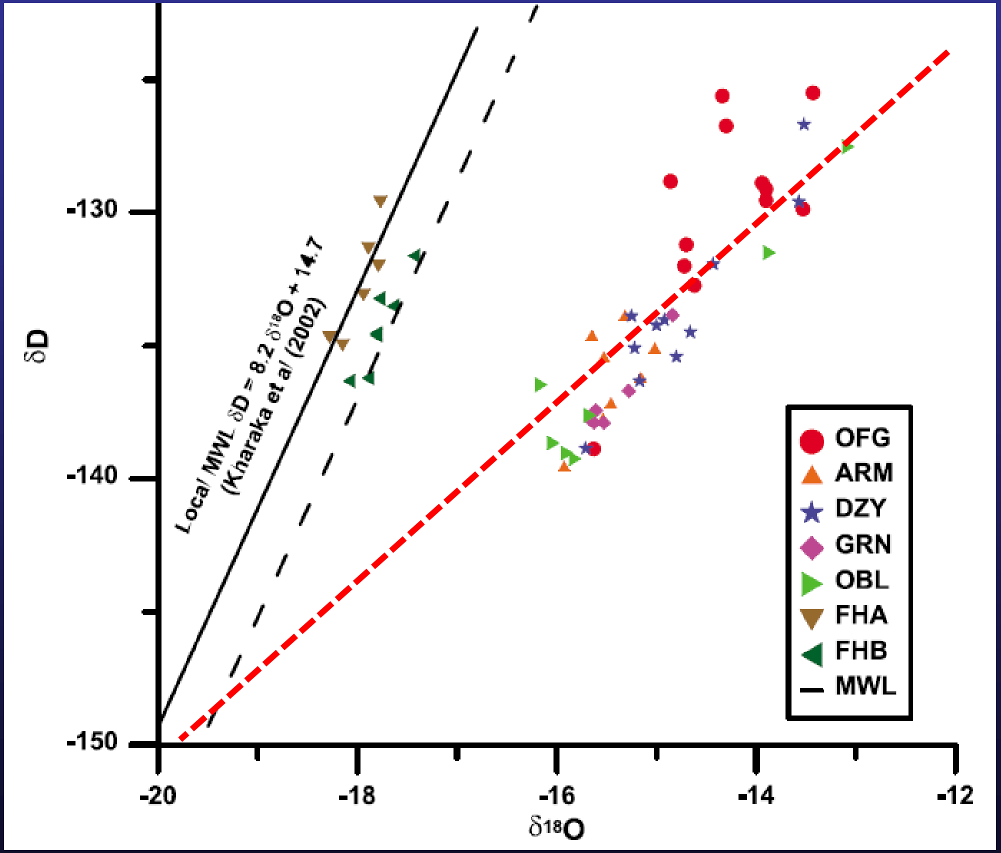
Examples of boiling and evaporation from Yellowstone's thermal basins

Heart Lake Geyser Basin



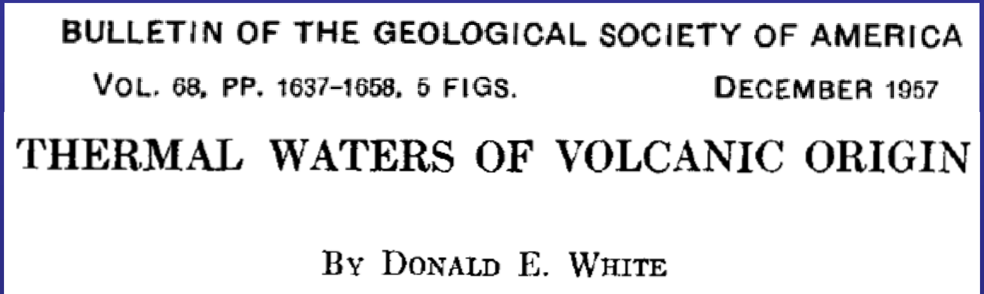
Lowenstern et al. G3 2012

Upper Geyser Basin



Hurwitz et al. G3 2012

Water and gas chemistry – insights on the current state of magmatism



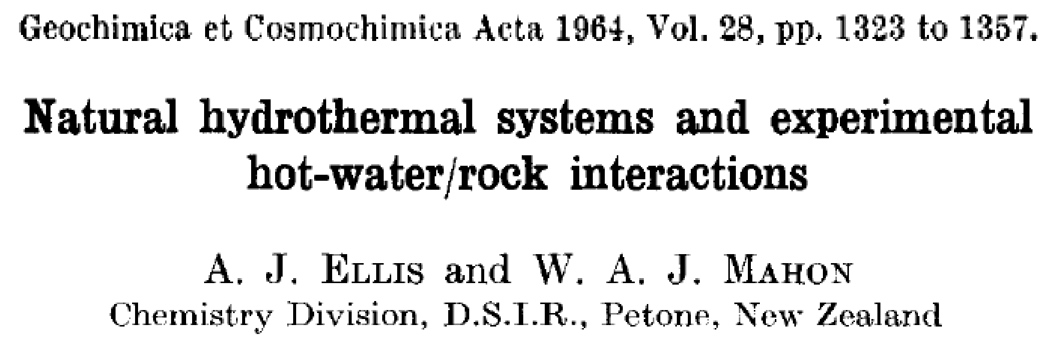
BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA

VOL. 68, PP. 1637–1658, 5 FIGS. DECEMBER 1957

THERMAL WATERS OF VOLCANIC ORIGIN

BY DONALD E. WHITE

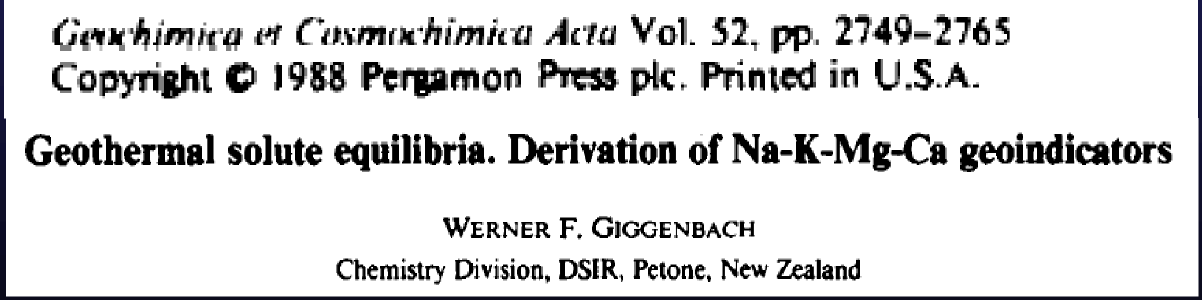
Research driven by geothermal energy and mineral exploration



Geochimica et Cosmochimica Acta 1964, Vol. 28, pp. 1323 to 1357.

Natural hydrothermal systems and experimental hot-water/rock interactions

A. J. ELLIS and W. A. J. MAHON
Chemistry Division, D.S.I.R., Petone, New Zealand



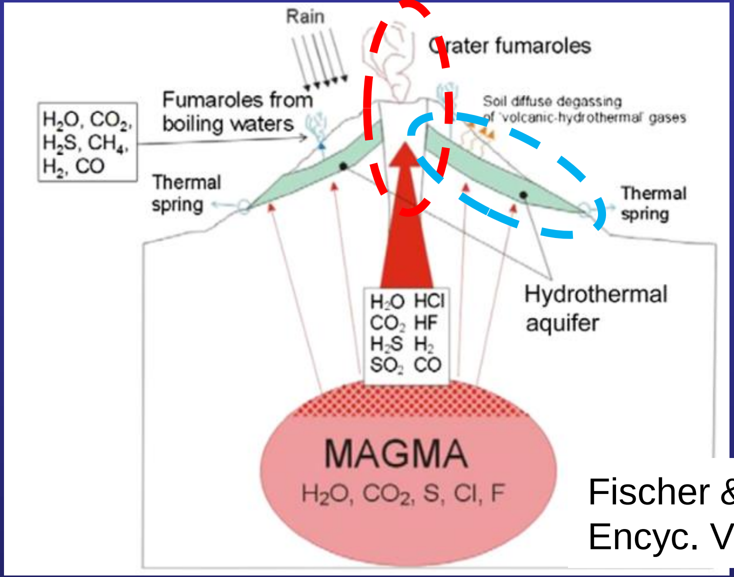
Geochimica et Cosmochimica Acta Vol. 52, pp. 2749–2765
Copyright © 1988 Pergamon Press plc. Printed in U.S.A.

Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators

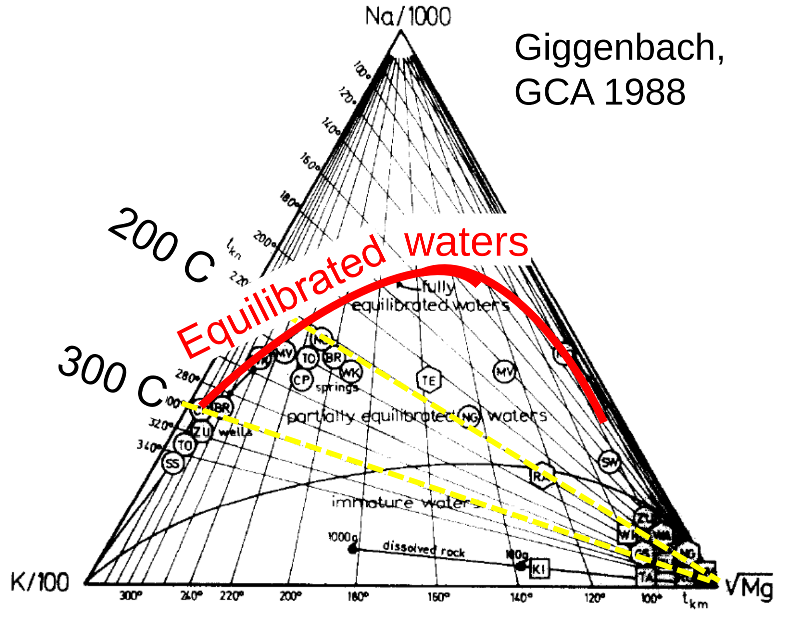
WERNER F. GIGGENBACH
Chemistry Division, DSIR, Petone, New Zealand

Water and gas chemistry – insights on the current state of magmatism

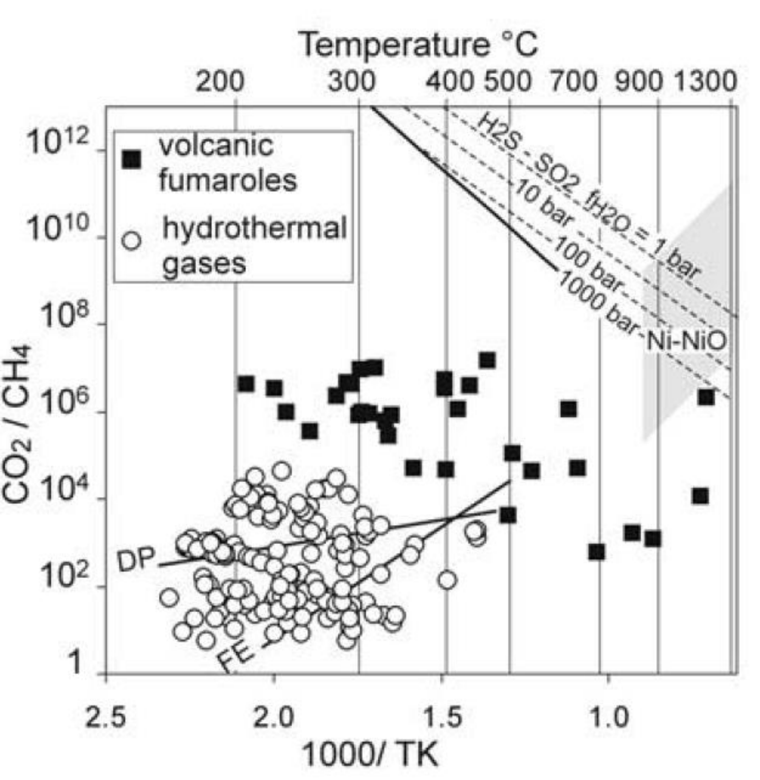
- Gas compositions are indicative of source (magma vs. hydrothermal)
- Dissolved cations equilibrate with rocks at 200-250 °C



Fischer & Chiodini, Encyc. Volc. 2015



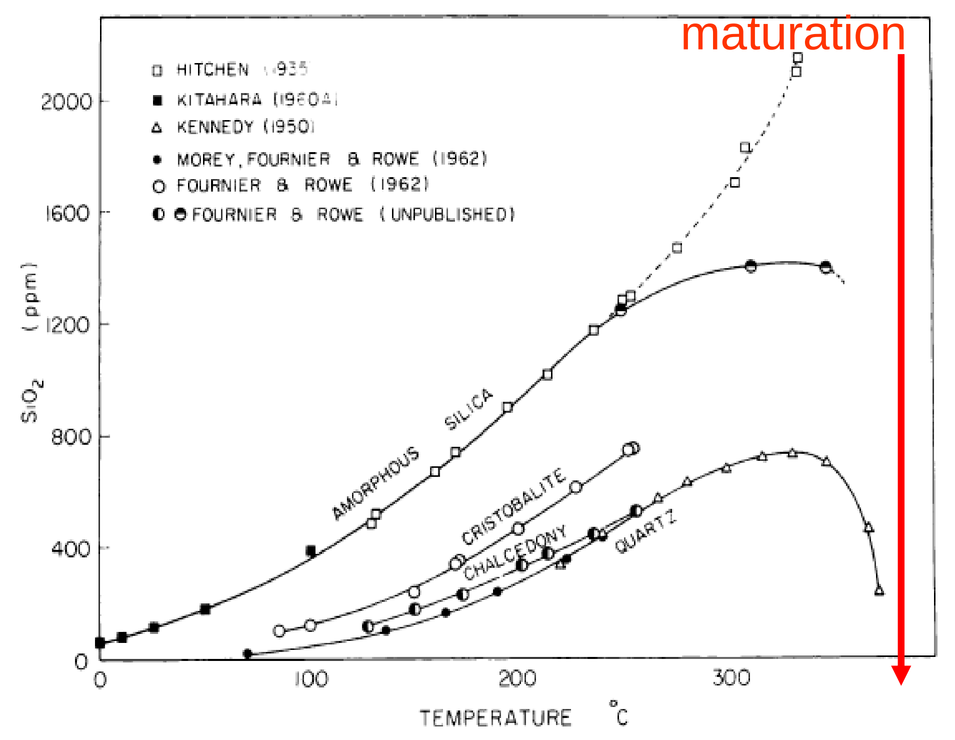
Giggenbach, GCA 1988



Chiodini, GRL 2009

Laboratory experiments – silica solubility

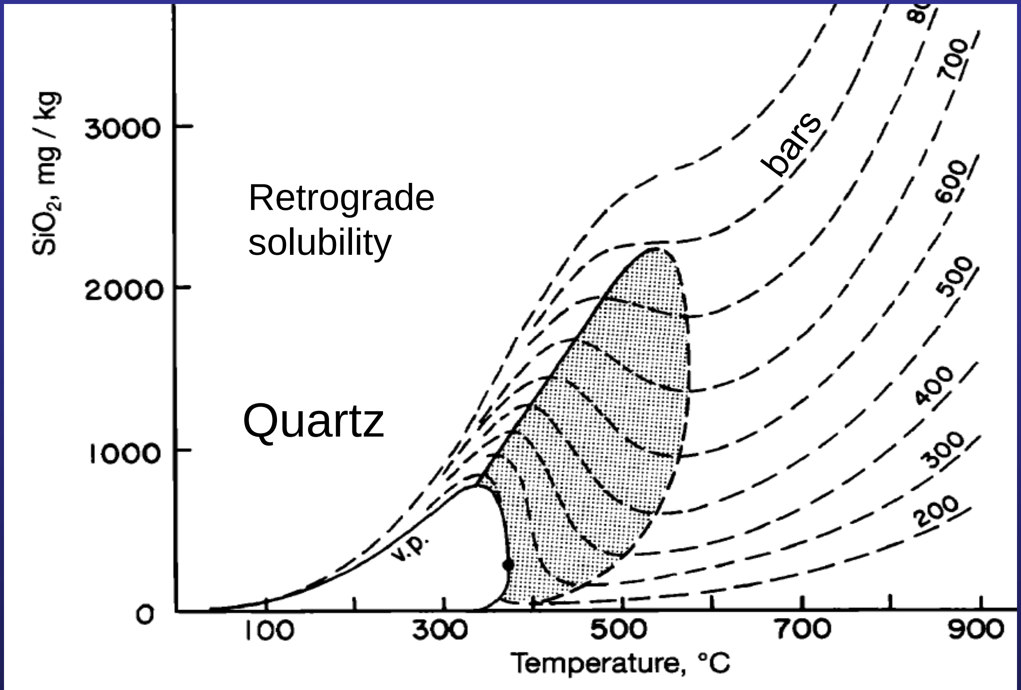
- **Why silica (SiO_2)?** Volcanic rocks have ~ 40-80 wt% SiO_2
- What happens when it **reacts with hot water**?

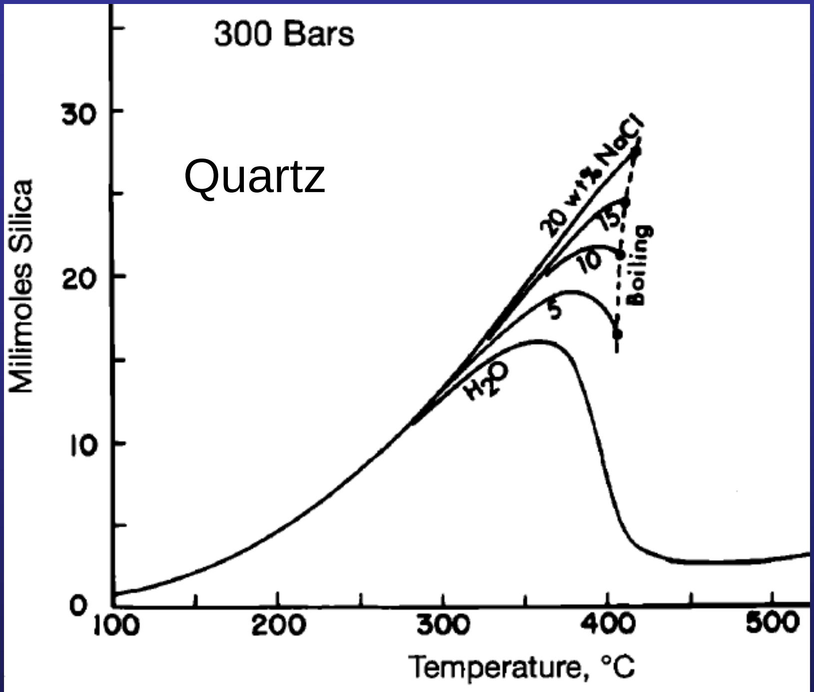


SiO_2 solubility decreases from amorphous -> Cristobalite-> Chalcedony -> quartz

Fournier and Rowe AJS 1966

Laboratory experiments – silica solubility



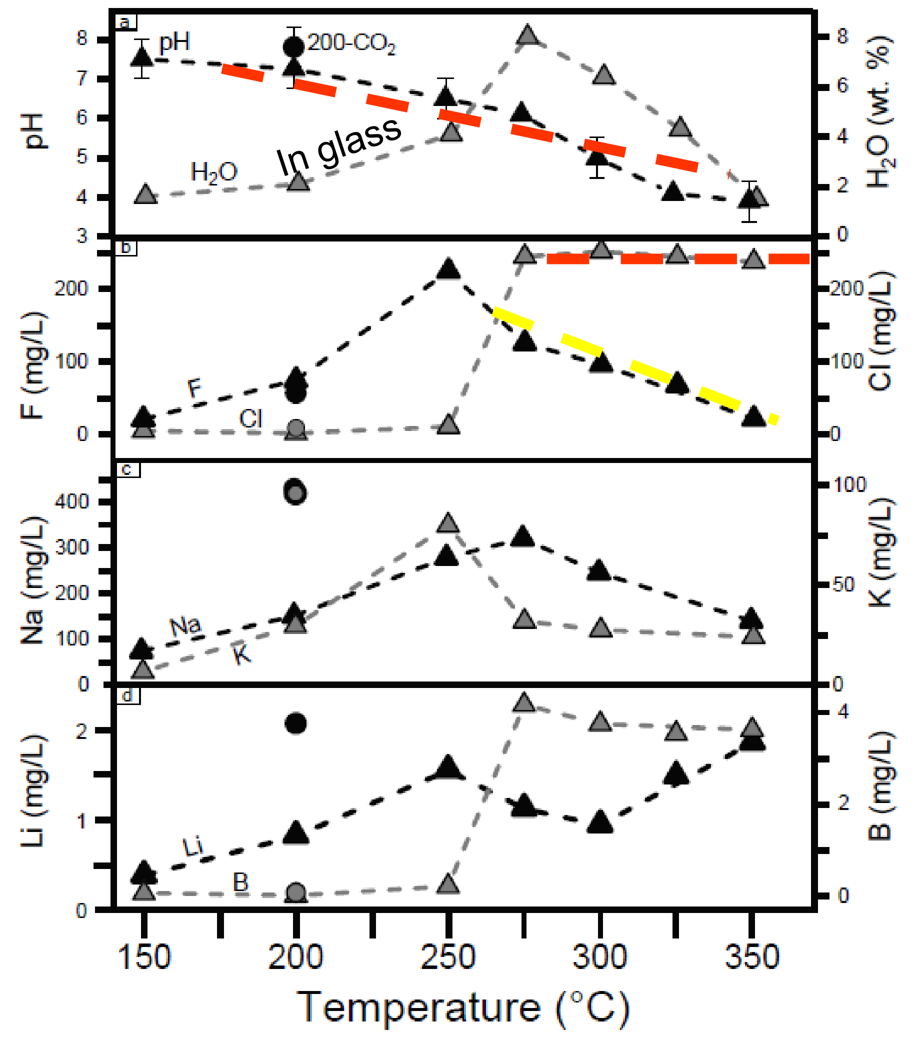


- Solubility has a minimum at ~ 400-450 °C
- Solubility increases with increasing salinity at ~ 350-450 °C

Fournier Econ Geol 1999

Laboratory experiments – reactivity of rhyolite at 150 °C -350 °C

Concentrations in reacted water



- Rhyolite hydrates with increasing temperature at 150-275 °C (max. 8.2 wt%). At T> 275 °C, secondary minerals form (mainly zeolite)
- At T ≥275 °C most **chlorine** is leached out of rhyolite and **fluorine** is incorporated into secondary minerals **(high Cl/F)**
- The stable isotopes of B, Li & Cl do not fractionate at 150 °C to 350 °C
- pH and alkalinity decrease with increasing temperature - (OH^-) is incorporated into zeolites

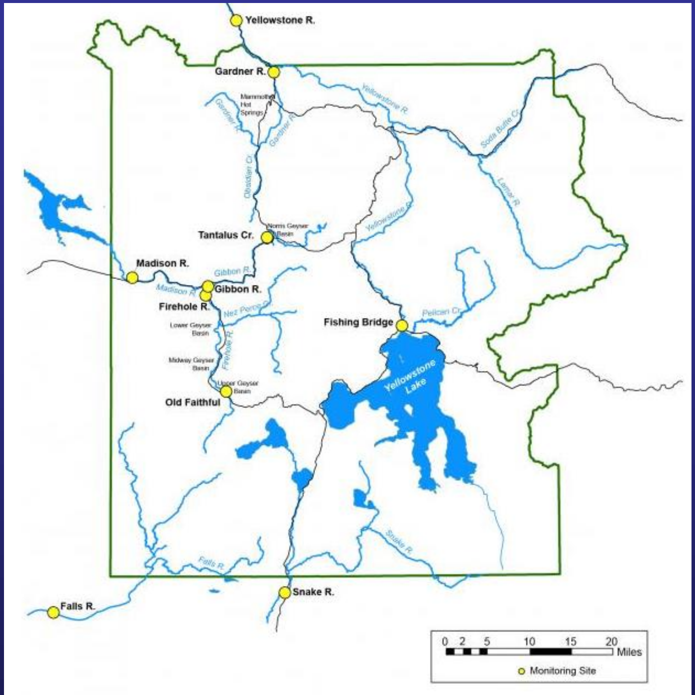
Cullen et al, GCA in press

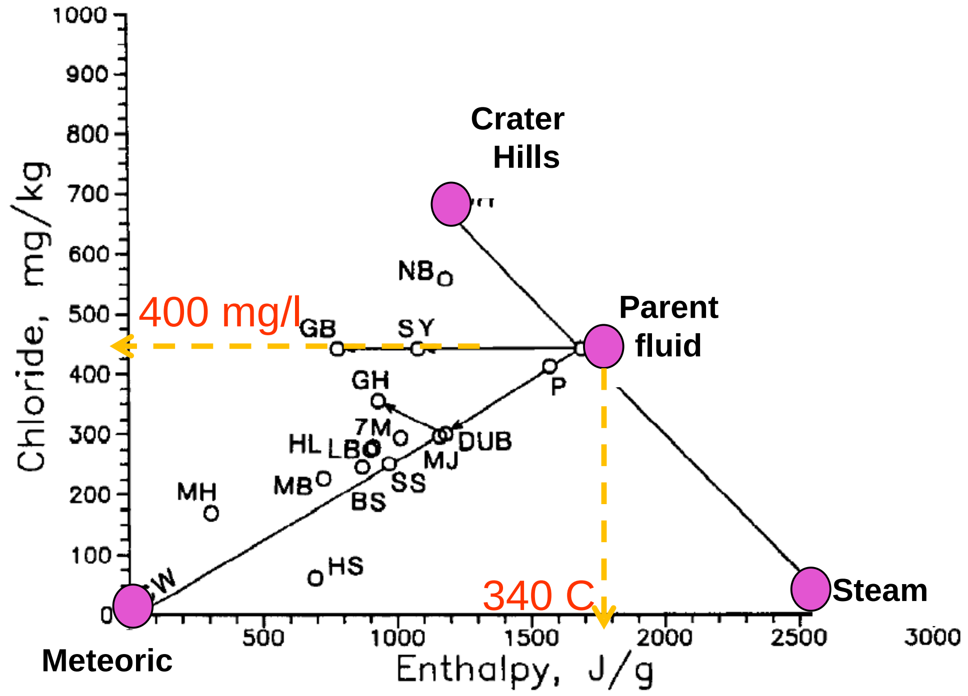
Inferences from heat flow measurements

Mechanisms of heat transport

- **Conduction** – spontaneous flow of thermal energy from higher to lower temperatures
- **Advection & convection** - transfer of heat through the movement of the medium’s particles (groundwater flow)
- **Radiation** - transfer of energy (heat) by the emission of electromagnetic radiation

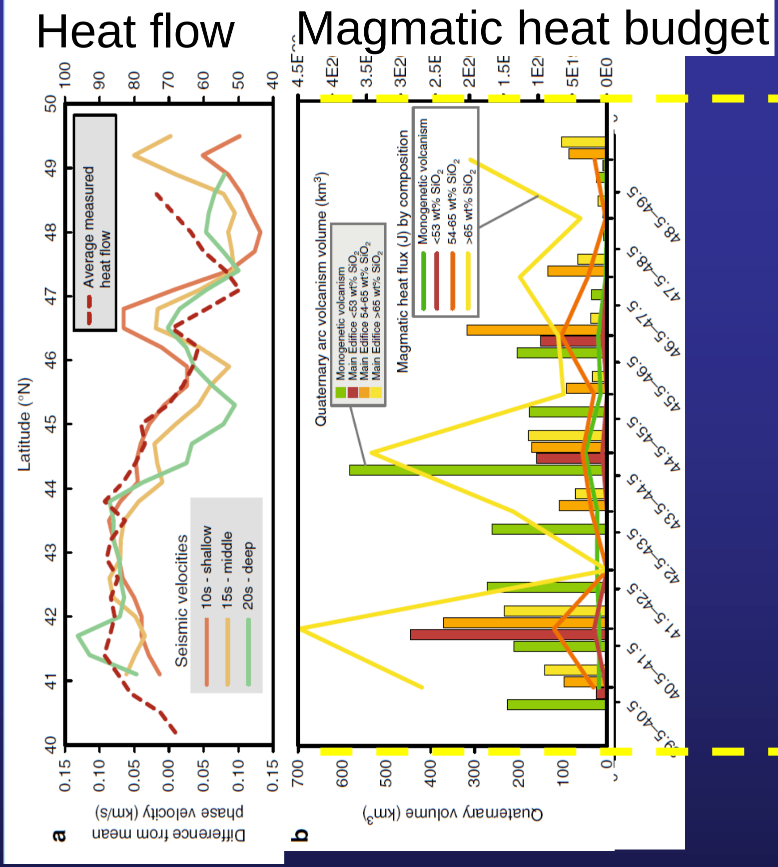
Cl-enthalpy method to estimate advective heat flow



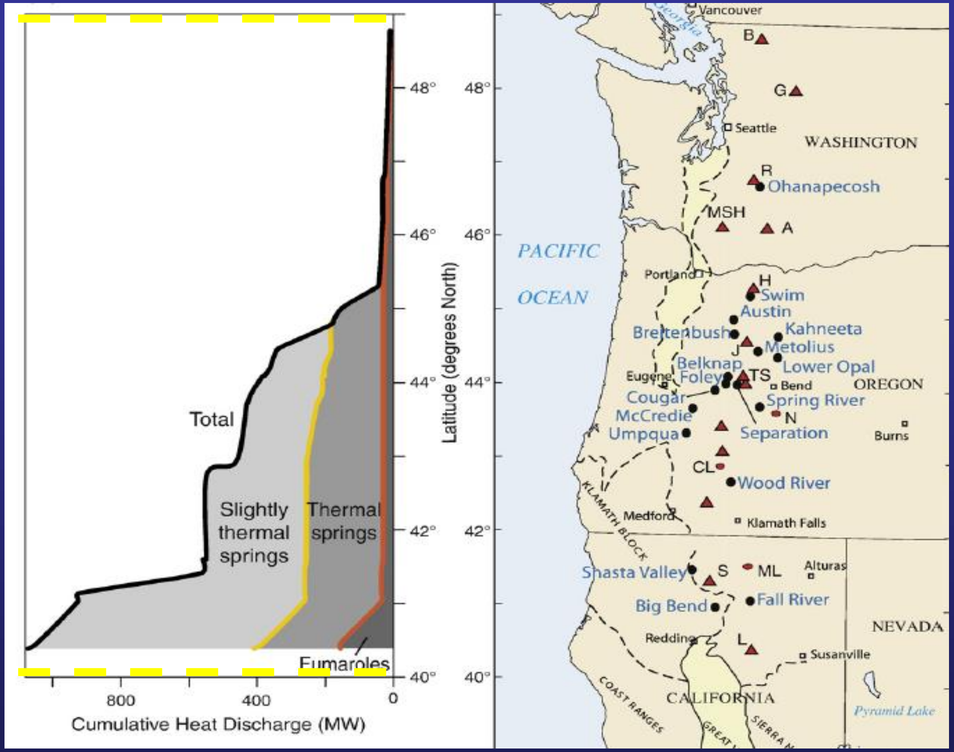


- The USGS & NPS operate a network of gages on all rivers draining the Yellowstone plateau
- Cl discharge from Yellowstone ~ 50,000 ton/year
- A “parent fluid” with 400 mg/l Cl & 340 °C
- Advective heat flow of 6.4 GW, or using a range of parameter values – 4-8 GW

Heat flow from volcanoes of the Cascades



Till et al. Nature Comm 2019



Ingebritsen & Mariner, JVGR 2010

“Slightly thermal” springs (a few degrees > ambient temp.) **~660 MW**

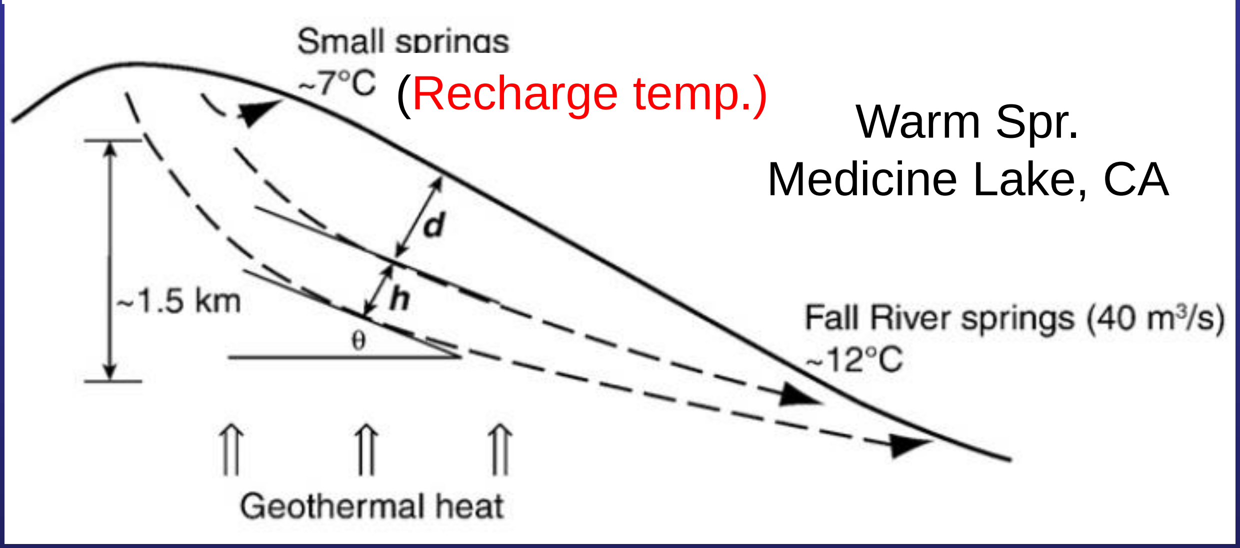
Thermal-spring ~240 MW

Fumaroles ~160 MW

Total ~1050 MW of “steady” heat(excluding transients)

Heat flow from the stratovolcanoes of the Cascades

Conversion of gravitational potential energy to heat



- The modest warming (5 °C) between high-elevation recharge and spring discharge equals 360 MW
- to interpret the temperature of cold springs, must account for : (1) **conversion of gravitational potential energy to heat through viscous dissipation**, (2) conduction of heat to or from the Earth's surface, and (3) geothermal warming

Manga & Kirchner WRR 2004

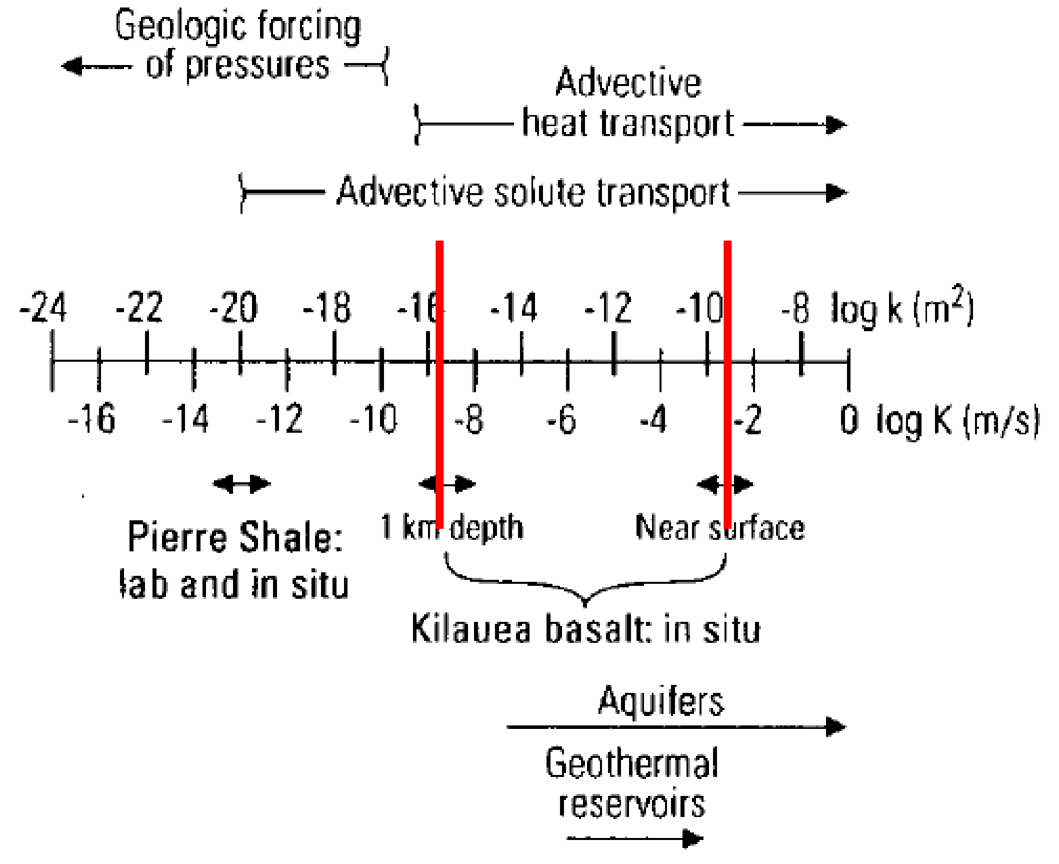
Summary of observations

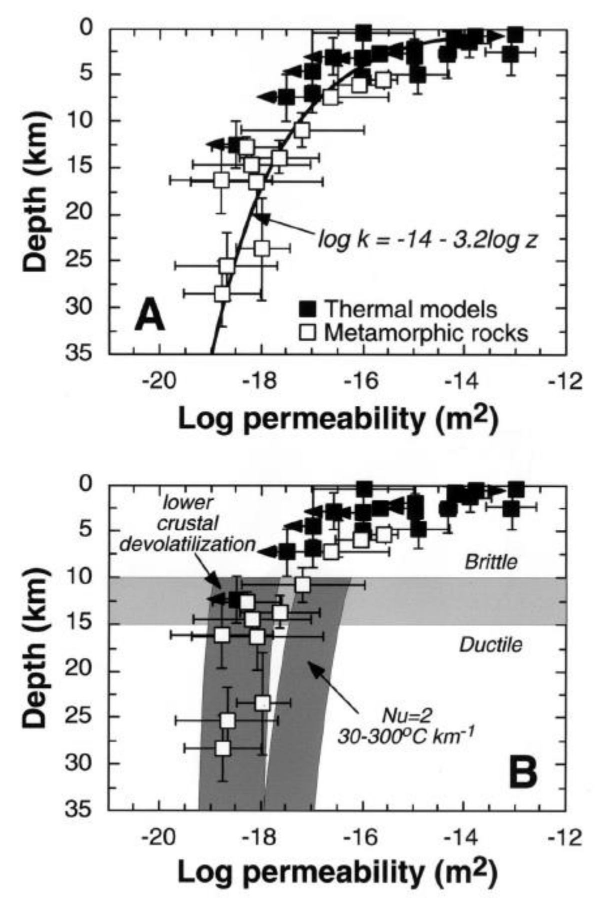
- **Drilling** –a narrow zone separating brittle and ductile rocks
- **Ore deposits** – magmatic vapors and hypersaline liquids are a source of metals
- **Geophysical imaging** – altered rocks, liquid and vapor saturation, salinity and temperature have unique physical manifestations
- **Broadbands**– multiple frequencies reflect many multiphase processes
- **Dense arrays** - track time-dependent 3-D migration of hydrothermal tremor
- **Seismic swarms** – defined spatial and temporal patterns
- **Water and gas chemistry** – water is meteoric, cations are mainly from crustal leaching of rocks and some anions are from magmatic gas condensation in groundwater
- **Laboratory experiments** –Silica solubility has a minimum at ~ 400-450 °C
- **Heat flow** – insights on the state of the magmatic system

Rock properties in continental hydrothermal systems

Scale-and depth-dependent permeability

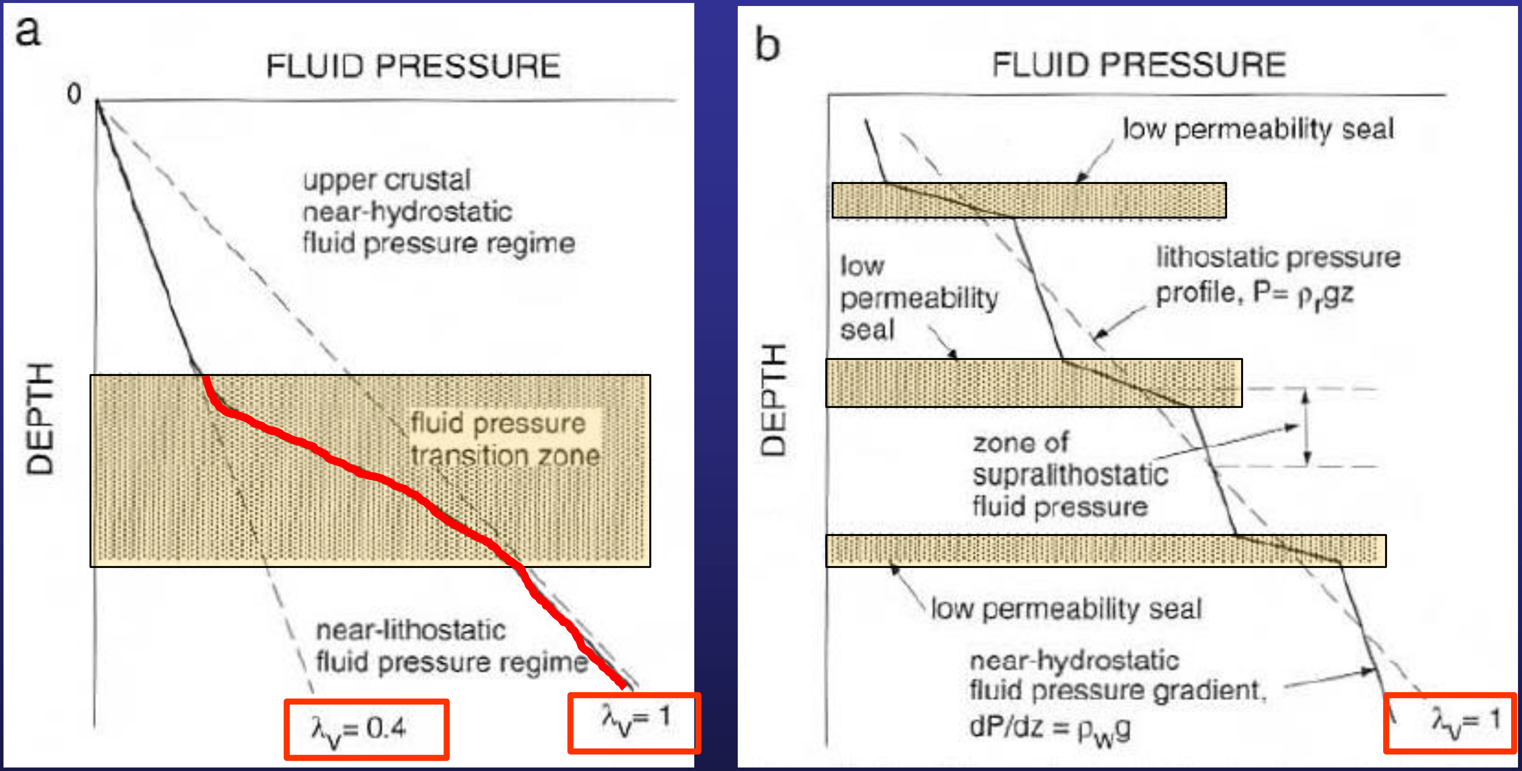
- In nature, permeability varies by ~17 orders of magnitude
- A mean crustal scale log permeability-depth curve suggests effectively constant permeability below 10-15 km





Manning & Ingebritsen, 1999

Heterogeneous permeability and fluid pressure distribution

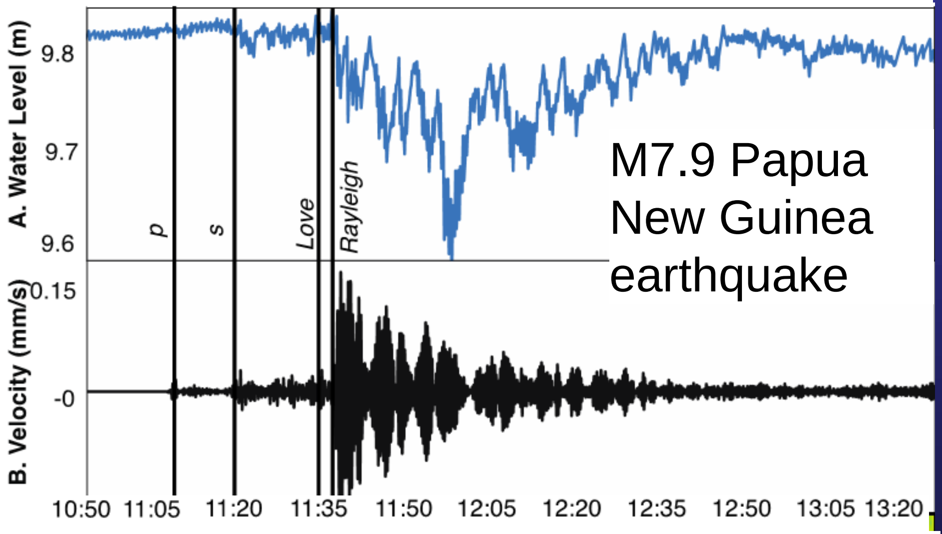


- **λ** - ratio of hydrostatic to lithostatic pressures
- Low-permeability layers can lead to separated convection cells and anomalous pressures

Cox, EconGeol, 2005

Transient permeability - water level and geyser response to earthquakes

Water level in a Long Valley Caldera well (CH-10B)

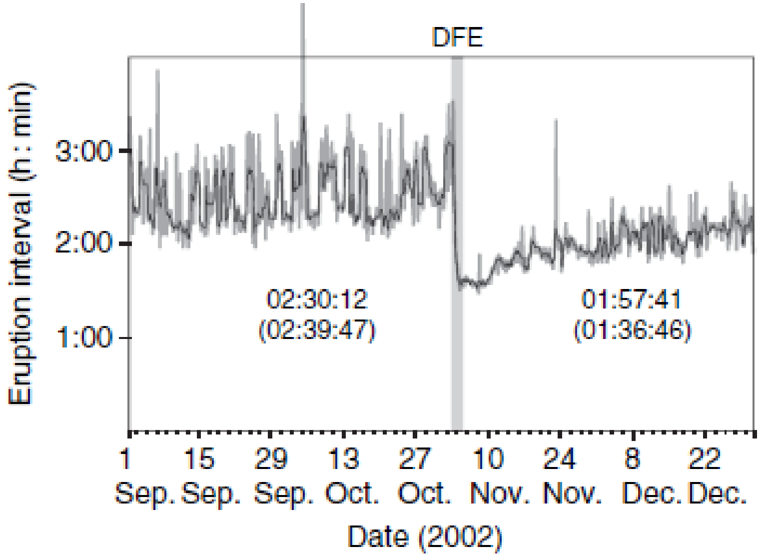


M7.9 Papua New Guinea earthquake

Time on 12/16/2016

Randolph-Flagg PhD; Berkeley 2019

Daisy Geyser, Yellowstone response to the **2002 Denali, Alaska** earthquake

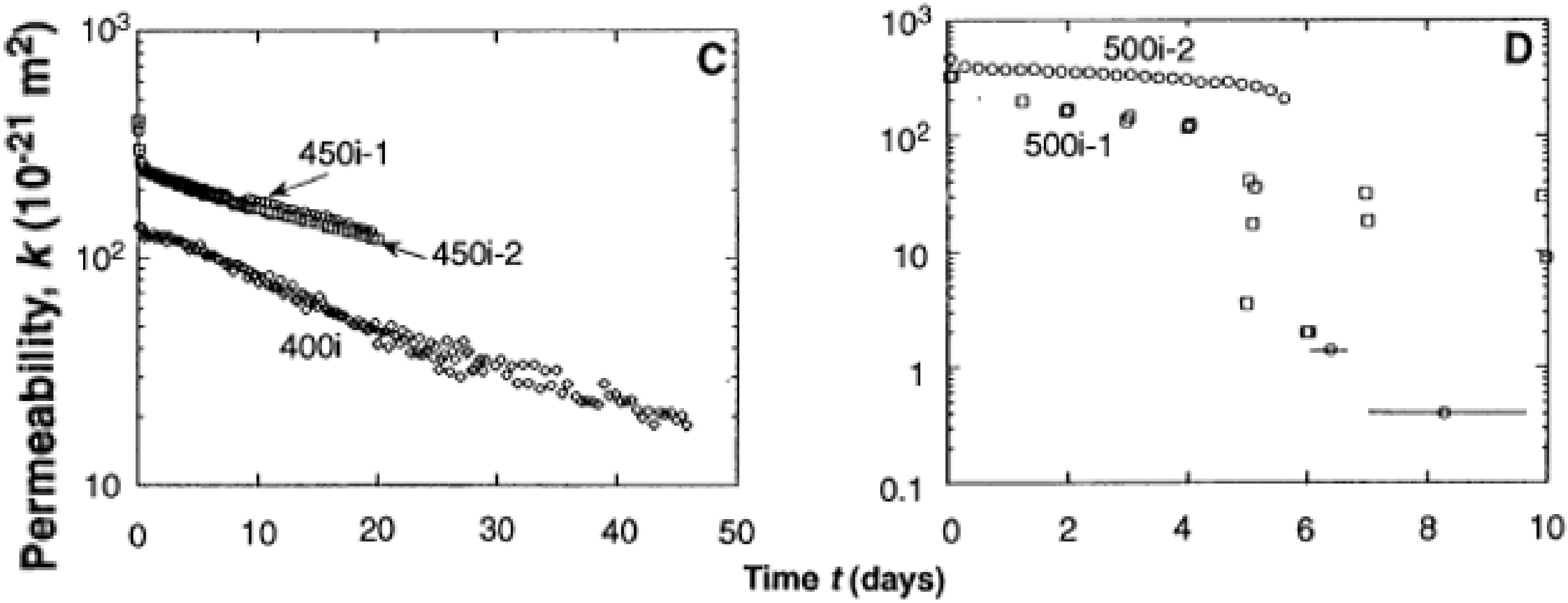


Husen et al. Geology 2004

- Instantaneous permeability change induced by long-period seismic surface waves
- Various types of responses and recoveries

Transient permeability – lab experiments

Permeability of intact Westerly granite



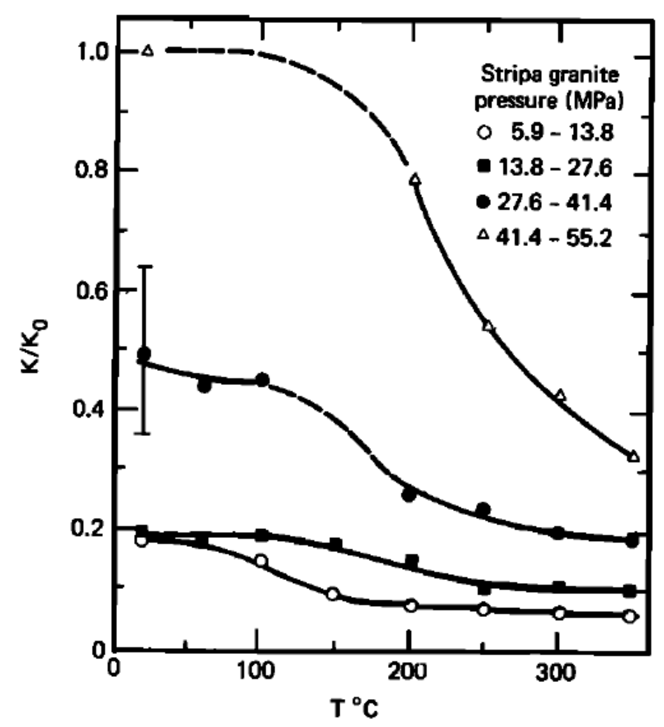
Permeability of rocks with hydrothermal flow can gradually decrease by orders of magnitudes in days to weeks

Moore et al. Science 1994

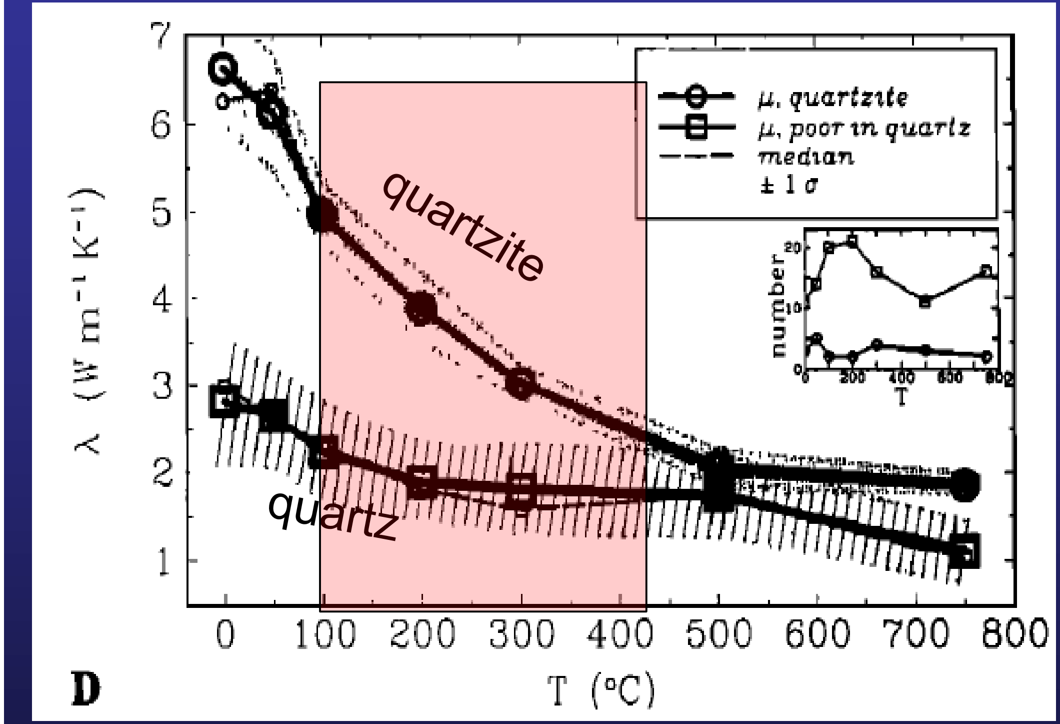
Other rock properties

Bulk Modulus

Thermal conductivity



Heard & Page JGR 1982

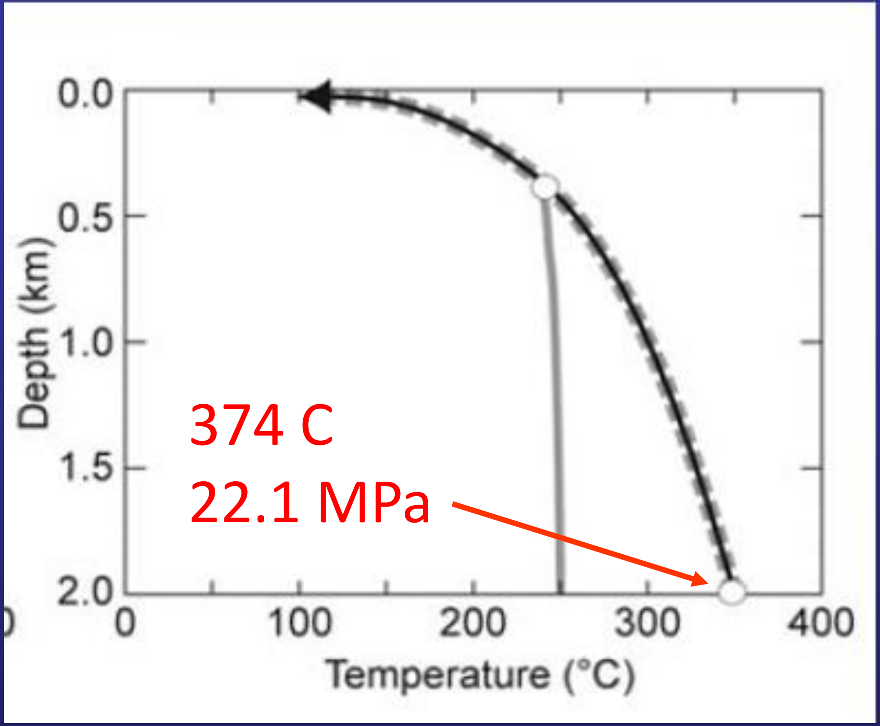


Clauser & Huenges 1995

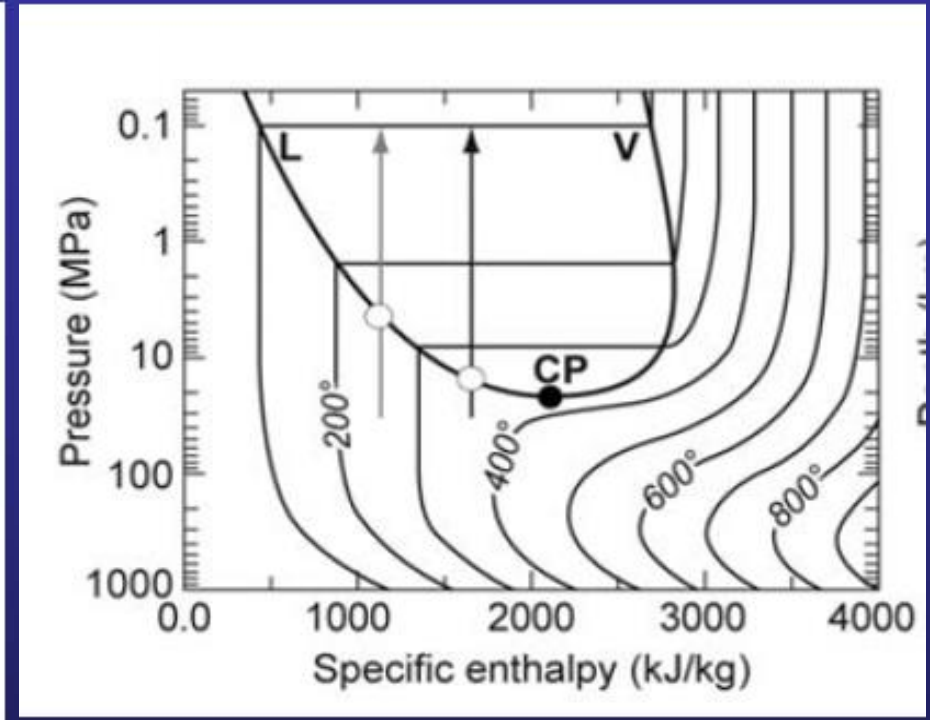
- Within the temperature range of hydrothermal systems, moduli are temperature dependent
- Thermal conductivity of (dry) rocks decrease with increasing temperature

Fluid properties in continental hydrothermal systems

Thermodynamic properties of pure water

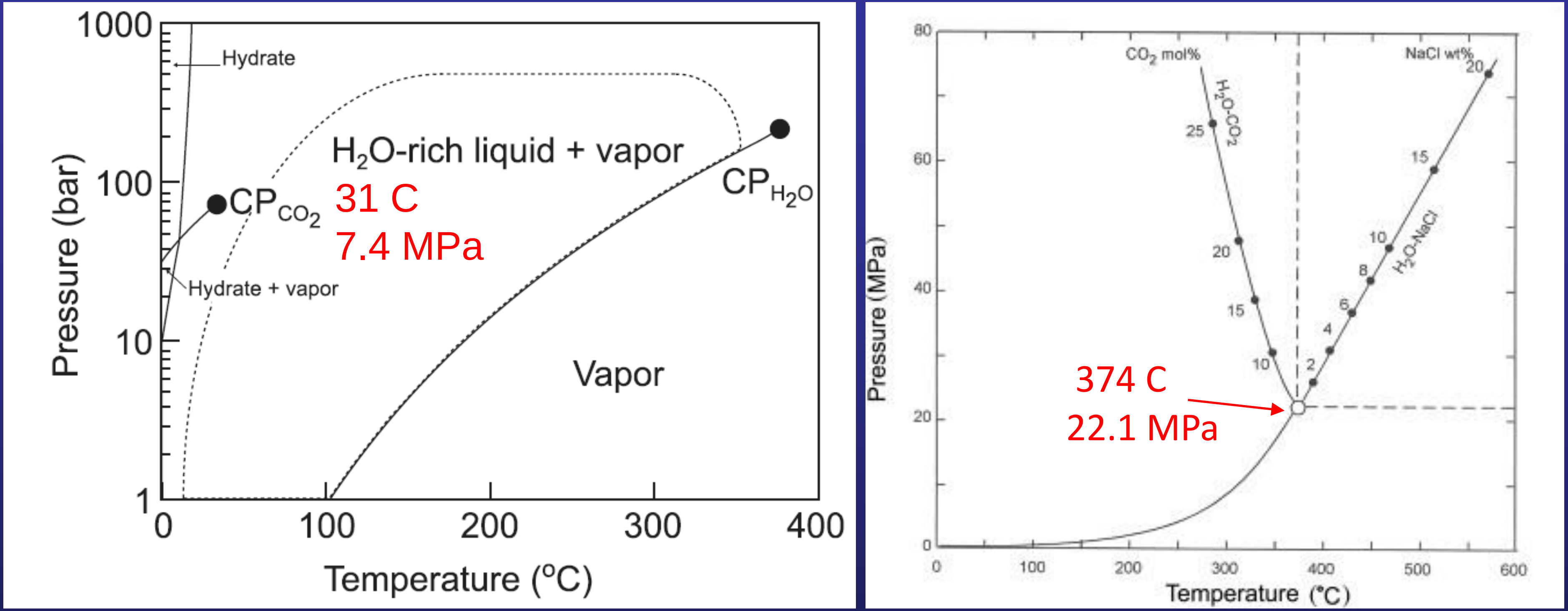


374 C
22.1 MPa



- At the **critical point** the properties of steam and liquid water merge
- **P-T diagrams** do not show details of the phase relations of the two-phase region
- In **pressure-enthalpy diagrams**, the mass fraction of each phase can be determined by the lever rule

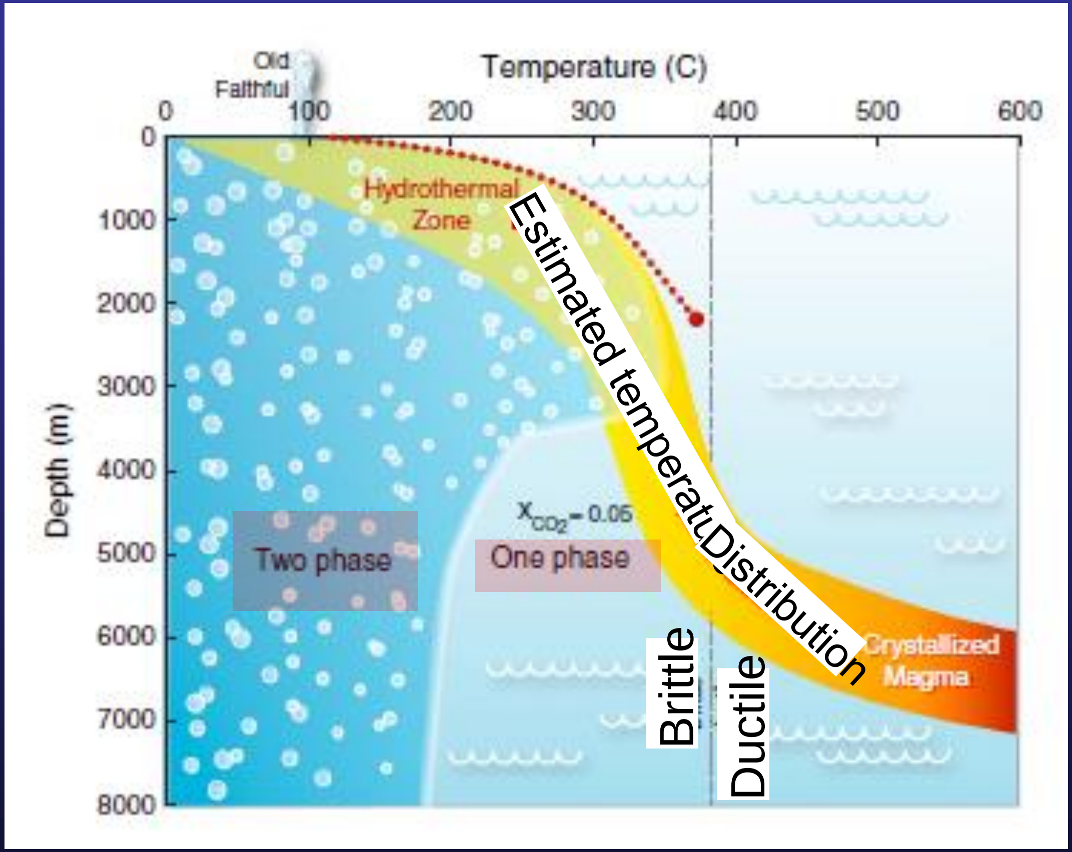
Multicomponent and multiphase fluids



Hutnak et al. JGR 2009

- In H_2O-CO_2 mixtures single and multiphase gas-rich and liquid-rich fluids exist over a range of P,T
- Dissolved salt increases the P,T of the critical point whereas dissolved gas reduces T and elevates P of the critical point

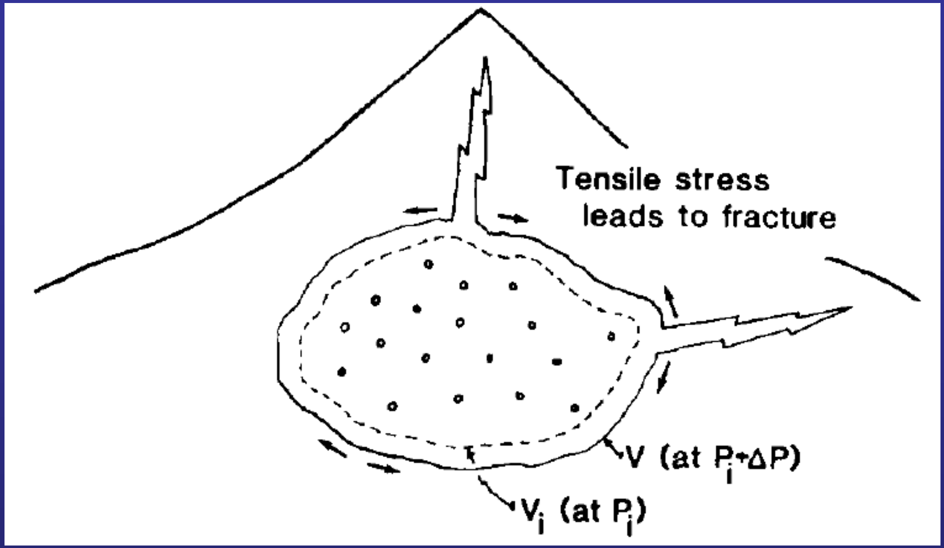
Phase distribution in Yellowstone's hydrothermal System



Lowenstern & Hurwitz., Elements 2008

- The high CO_2 flux requires a mixed steam–CO_2 vapor phase in the upper ~4 km
- Vapor saturated conditions affect pressure distribution between magma and the ground surface
- Vapor-dominated reservoirs form above areas of deep boiling and degassing

Multiphase fluid compressibility



Tait et al EPSL 1989

$$\beta = \frac{1}{V} \cdot \frac{\Delta V}{\Delta P}$$

A liquid + steam mixture in porous media is more compressible than a single phase (steam or liquid]

At 250 °C

$\beta_t = 0.9$ bar^{-1} (steam + liquid)

$\beta_s = 0.03$ bar^{-1} (steam)

$\beta_t = 1.3 \times 10^{-4}$ bar^{-1} (liquid)

Grant and Sorey WRR 1989

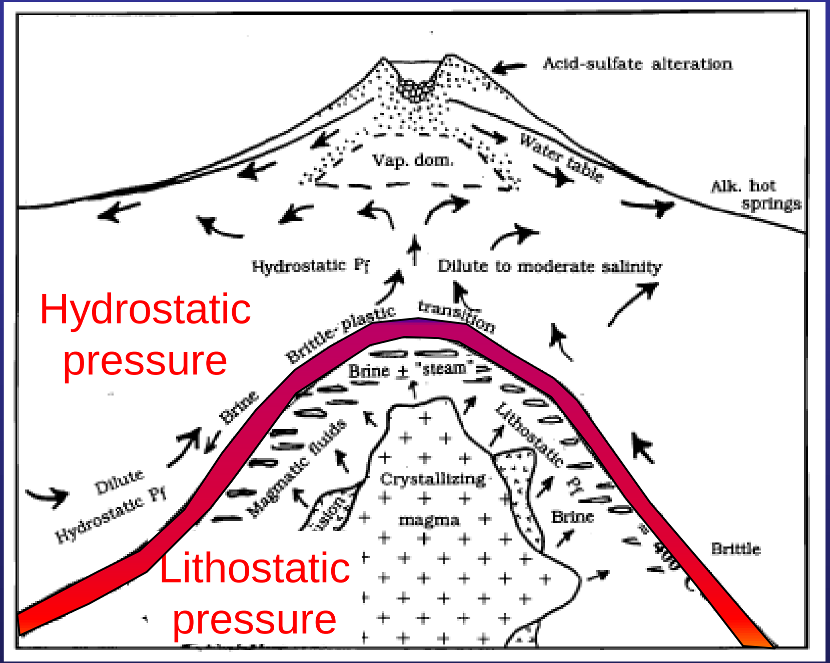
Summary - rock and fluid properties

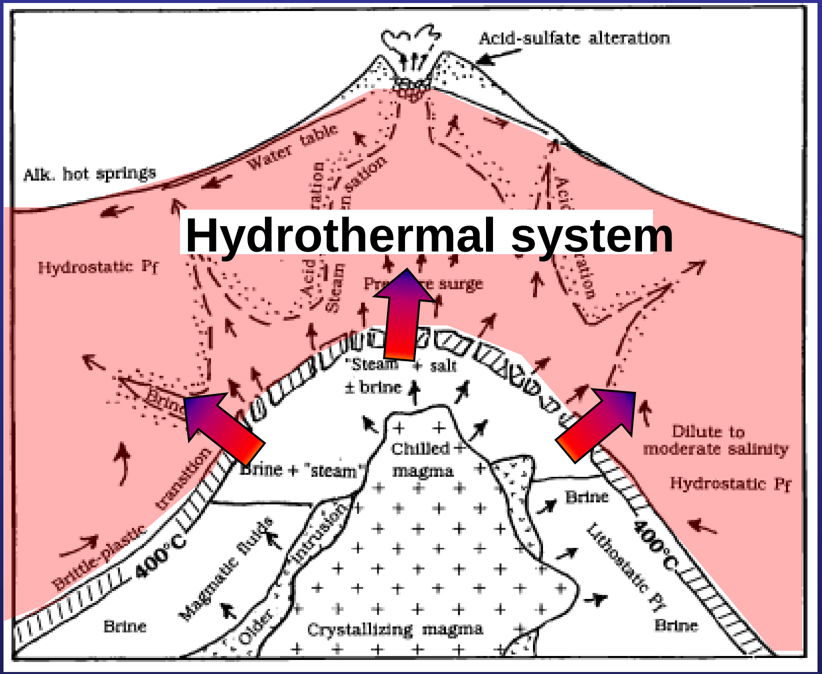
- **Permeability varies by ~17 orders of magnitude** in nature
- **Low-permeability layers** can lead to anomalously **high pressures**
- **Permeability is highly transient** and **is modified** by earthquakes and precipitation and dissolution reactions
- **Moduli and thermal conductivity are temperature dependent**
- In H_2O-CO_2 mixtures single and **multiphase gas-rich and liquid-rich fluids exist over a larg P,T range**
- **Dissolved salts increase the pressure and temperature of the critical point** whereas CO_2 reduces the temperature of the critical point
- **The compressibility of a liquid + steam mixture is high**

Putting it all together:

Heat and volatile transport from magma to the ground surface

Heat and volatile transport from magma to the hydrothermal System

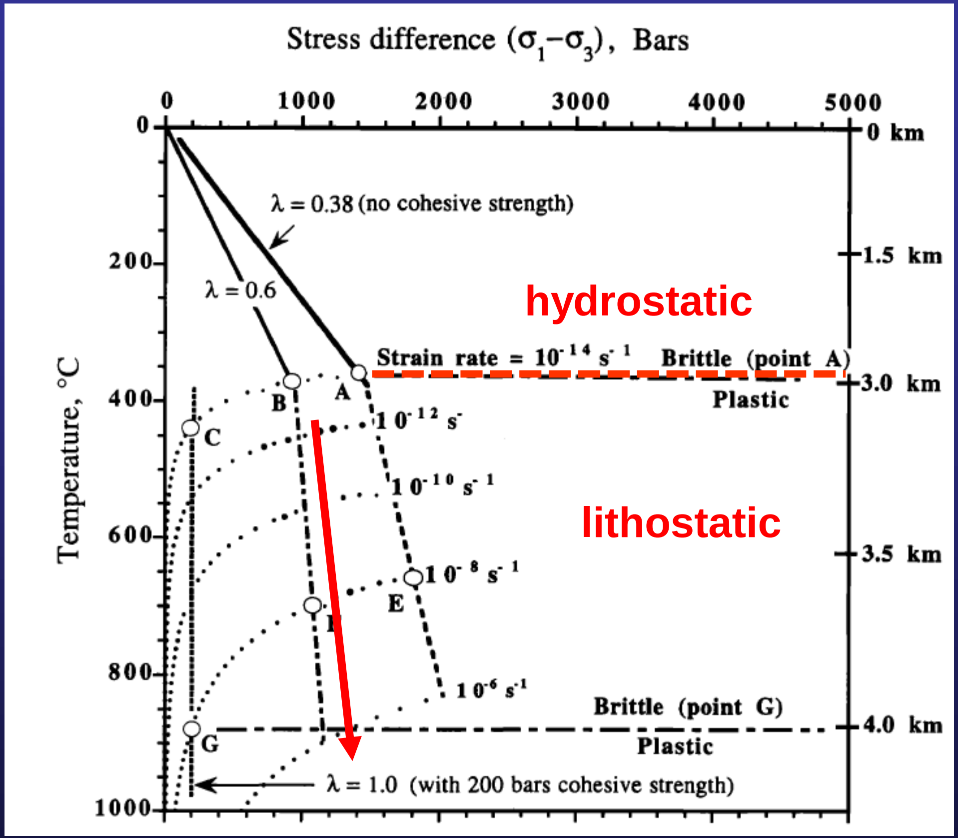




- The brittle-ductile transition (BDTZ) coincides with a thin (<100 m) conductive boundary layer (CBL) with a thickness proportional to the heat flux across it
- Episodic breach of the BDTZ – transport of magmatic volatiles and heat
- As magma cools, the CBL migrates downward - deeper hydrothermal circulation

Fournier, Econ Geol 1999

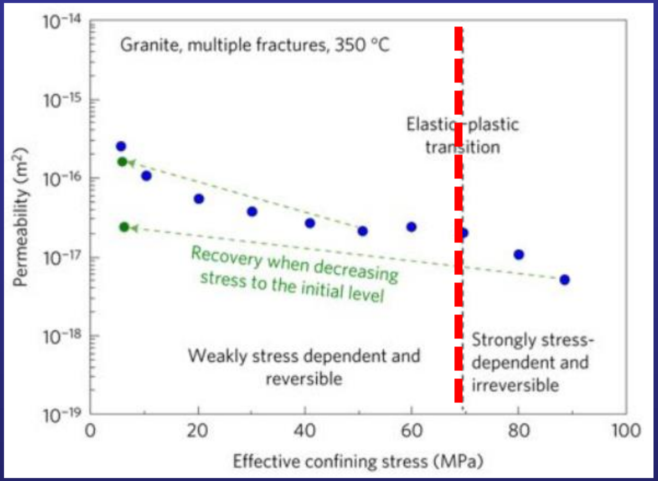
Mechanics of the BDTZ

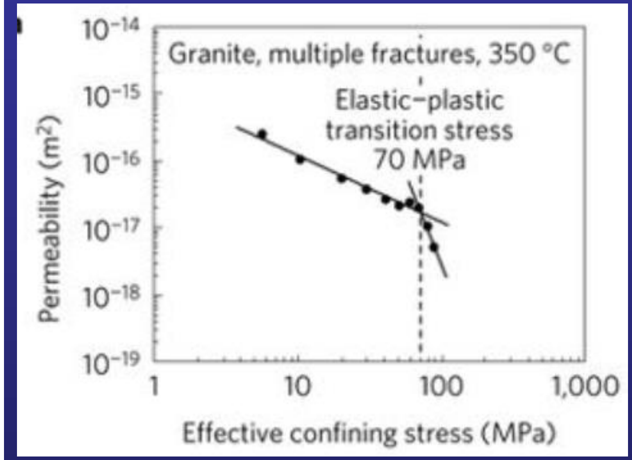


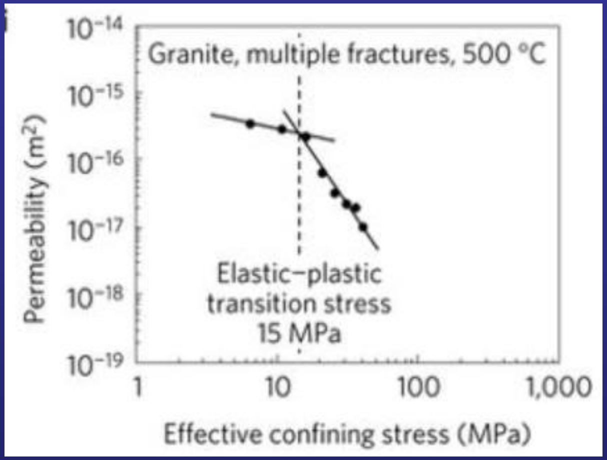
- Ductile and low permeability rocks below the BDTZ & brittle rocks above
- The BDTZ is assumed **at ~ 400 °C**. Coincides with the maximum temperature of MOR vents, geothermal wells and minimum SiO_2 solubility
- Can range from 260 °C for wet quartz to ~700 °C for dry OPX
- **A strain rate increase can cause ductile rocks to become brittle** and undergo shear failure

Fournier, Econ Geol 1999

Permeability of fractured granite as a function of confining stress





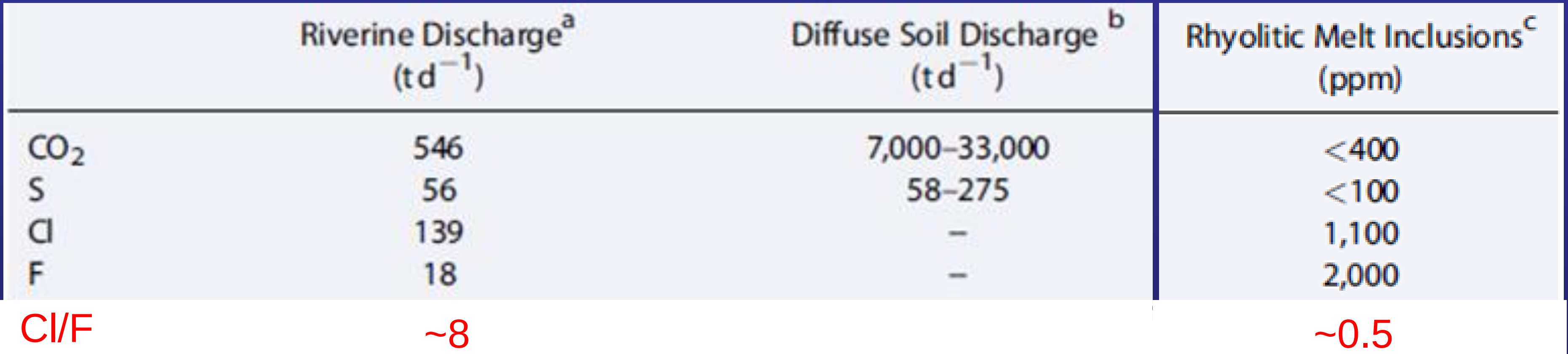


- BDTZ is not the first-order control on rock permeability
- At 350–500 °C, permeability **transitions** from being weakly stress-dependent and reversible to being strongly stress-dependent and irreversible

Watanabe et al., Nature Geo 2017

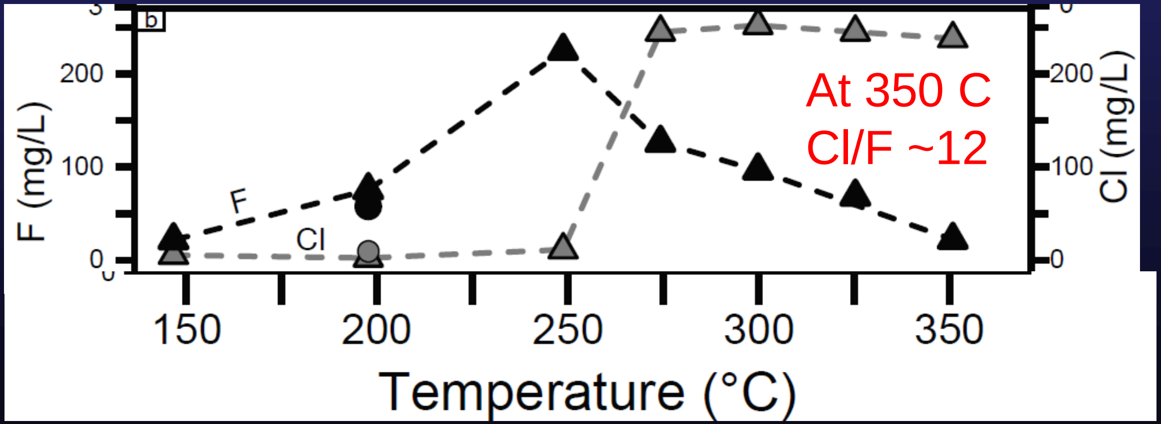
Sources and sinks of energy and mass in the hydrothermal system

Volatiles dissolved in magma vs. discharge from the hydrothermal system – sources and sinks



	Riverine Discharge[a] (td^{-1})	Diffuse Soil Discharge[b] (td^{-1})	Rhyolitic Melt Inclusions[c] (ppm)
CO_2	546	7,000–33,000	<400
S	56	58–275	<100
Cl	139	–	1,100
F	18	–	2,000
Cl/F	~8		~0.5

- Large sink of F or source of Cl in the shallow crust



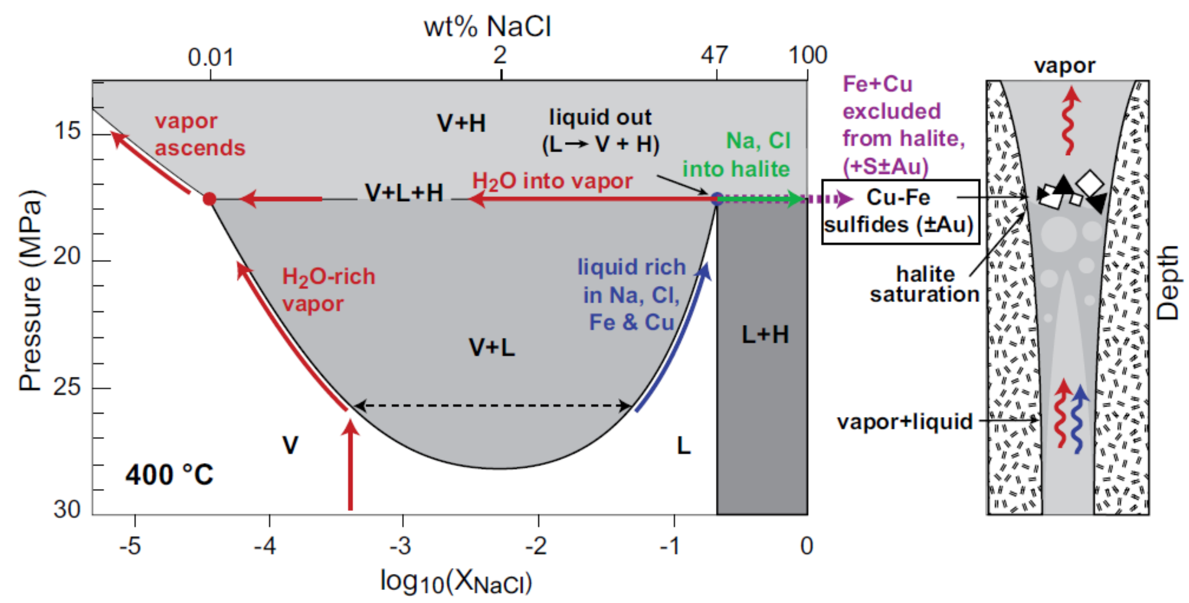
At 350 C
Cl/F ~12

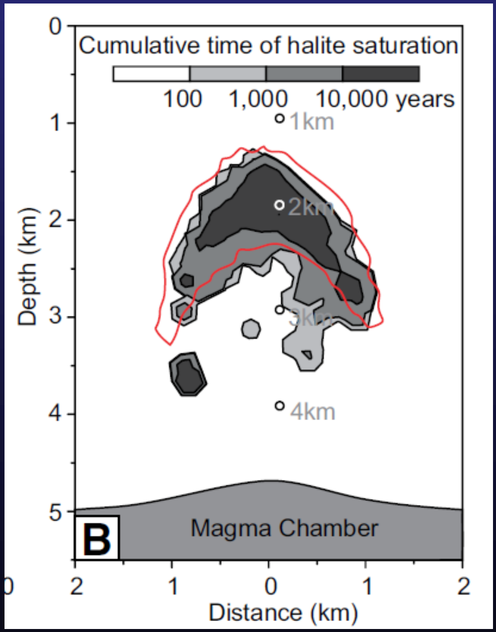
Cullen et al., GCA in press

Lowenstern & Hurwitz., 2008

Halite precipitation and mineralization

- Saline fluids ascending from plutons undergo phase separation into high salinity brine and low salinity vapor
- Fluid inclusion from porphyry deposits contain evidence for solid salt (halite) precipitation from ore-forming solutions
- Salt precipitation changes the permeability of the system

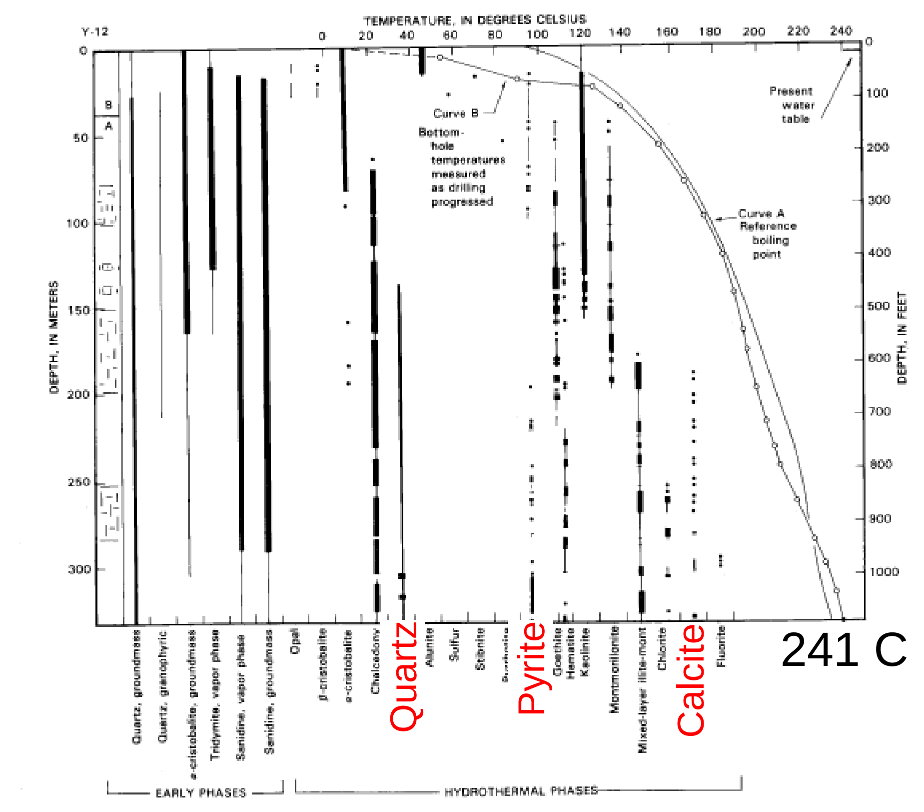




Lecumberri-Sanchez et al. Geology 2015

Hydrothermal rock alteration

- **Replacement of high-temperature glass and primary minerals** with secondary minerals resulting from reaction with volatile-rich fluids
- Can be a **sink or source** for some volatiles and cations modifying the composition of the residual fluid

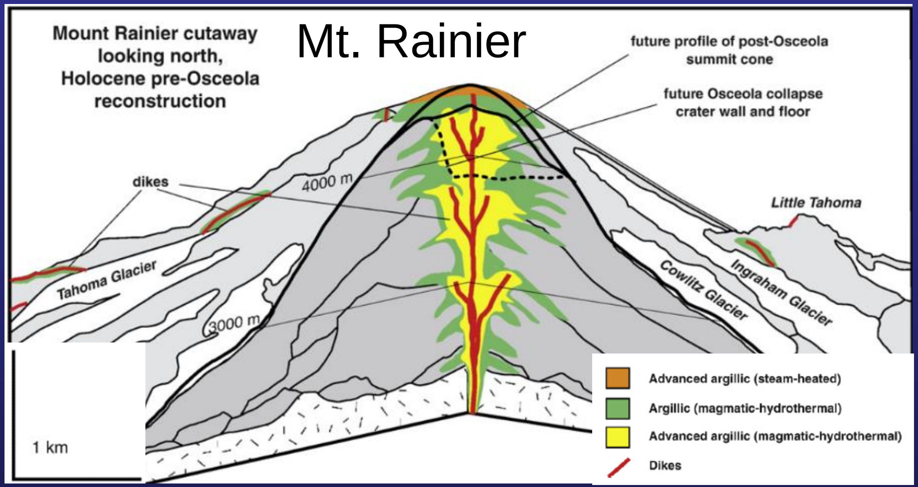


Y-12, Norris Geyser Basin Yellowstone

White et al. 1988

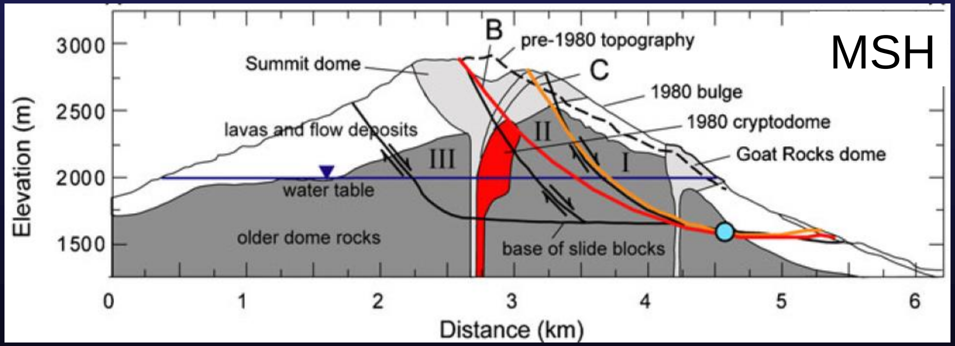
Flank collapse of hydrothermally altered rocks

- More than 200 steep stratovolcanoes collapsed in historical times
- Rock shear strength is decreased by acid sulfate-argillic alteration



John et al JVGR 2008

Large flank collapses of weak, hydrothermally altered parts of Mt. Rainier generated far-traveled lahars in the Holocene



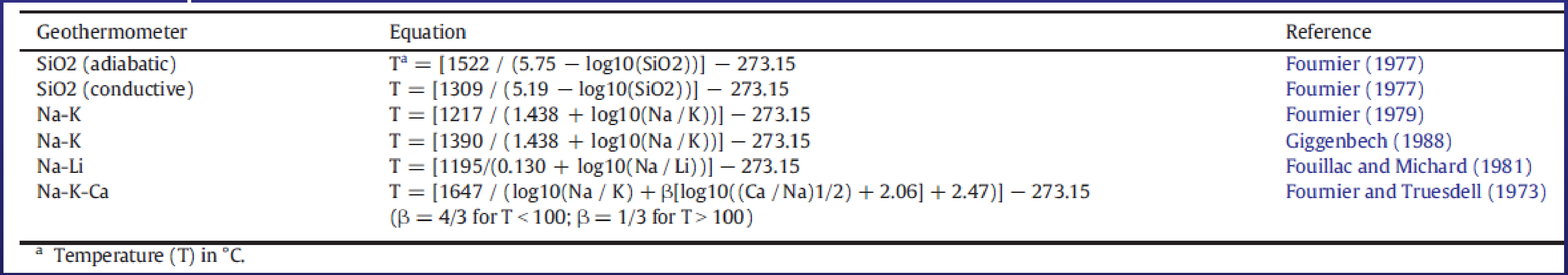
Reid et al BV 2010

The 1980 failure shear surfaces were not localized in weak altered rocks, but primarily in pervasively shattered older dome rocks

Water and gas geothermometry

What are the equilibrium temperatures of water-rock reactions?

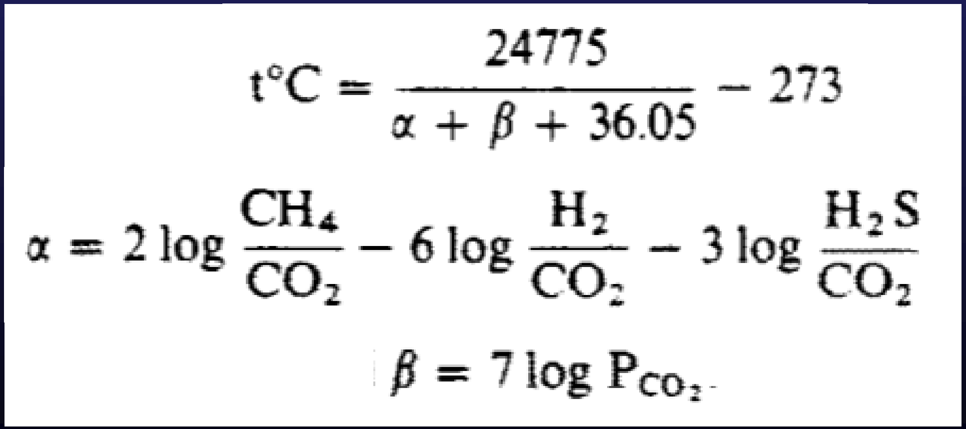
“Classical” geothermometers are based on the concentration of dissolved silica (SiO_2) in equilibrium with silica polymorphs or on the ratios of cations in equilibrium with feldspar



Geothermometer	Equation	Reference
SiO2 (adiabatic)	$T^a = [1522 / (5.75 - \log10(SiO2))] - 273.15$	Fournier (1977)
SiO2 (conductive)	$T = [1309 / (5.19 - \log10(SiO2))] - 273.15$	Fournier (1977)
Na-K	$T = [1217 / (1.438 + \log10(Na / K))] - 273.15$	Fournier (1979)
Na-K	$T = [1390 / (1.438 + \log10(Na / K))] - 273.15$	Giggenbech (1988)
Na-Li	$T = [1195/(0.130 + \log10(Na / Li))] - 273.15$	Fouillac and Michard (1981)
Na-K-Ca	$T = [1647 / (\log10(Na / K) + \beta[\log10((Ca / Na)1/2) + 2.06] + 2.47)] - 273.15$ ($\beta = 4/3$ for $T < 100$; $\beta = 1/3$ for $T > 100$)	Fournier and Truesdell (1973)

[a] Temperature (T) in °C.

Gas geothermometry



$$t°C = \frac{24775}{\alpha + \beta + 36.05} - 273$$

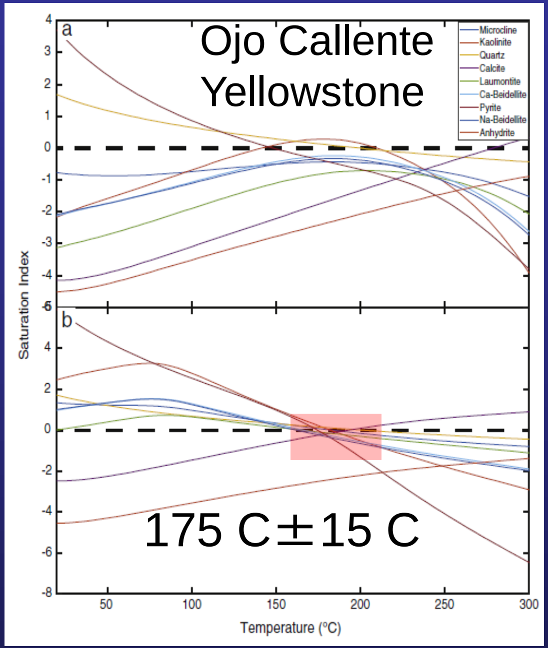
$$\alpha = 2 \log \frac{CH_4}{CO_2} - 6 \log \frac{H_2}{CO_2} - 3 \log \frac{H_2S}{CO_2}$$

$$\beta = 7 \log P_{CO_2}.$$

Based on the concentration and thermodynamic equilibrium of gas species

D'Amore & Panichi, GCA1980

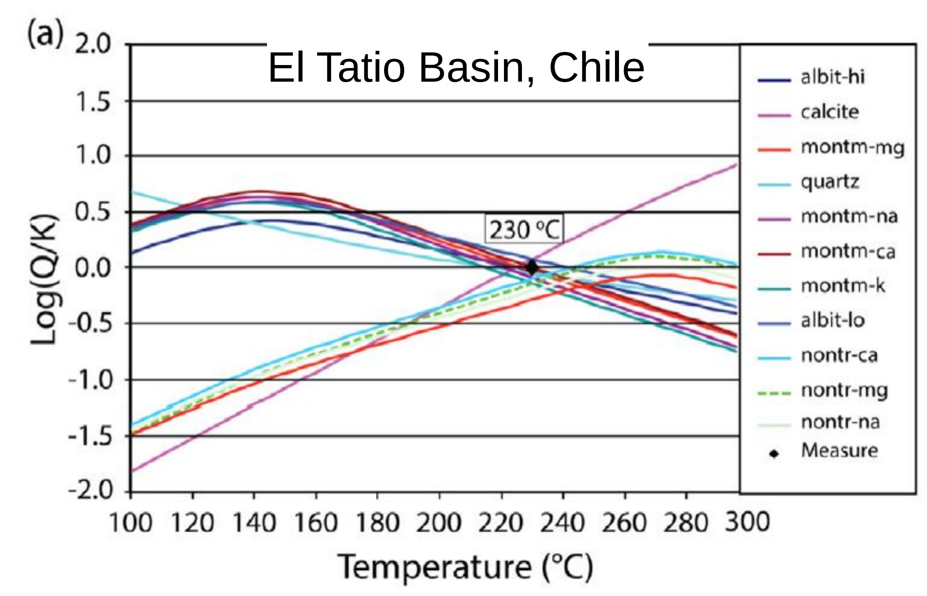
Thermodynamic models of fluid-mineral equilibria



Ojo Callente Yellowstone

175 C±15 C

King et al, JVGR 2016

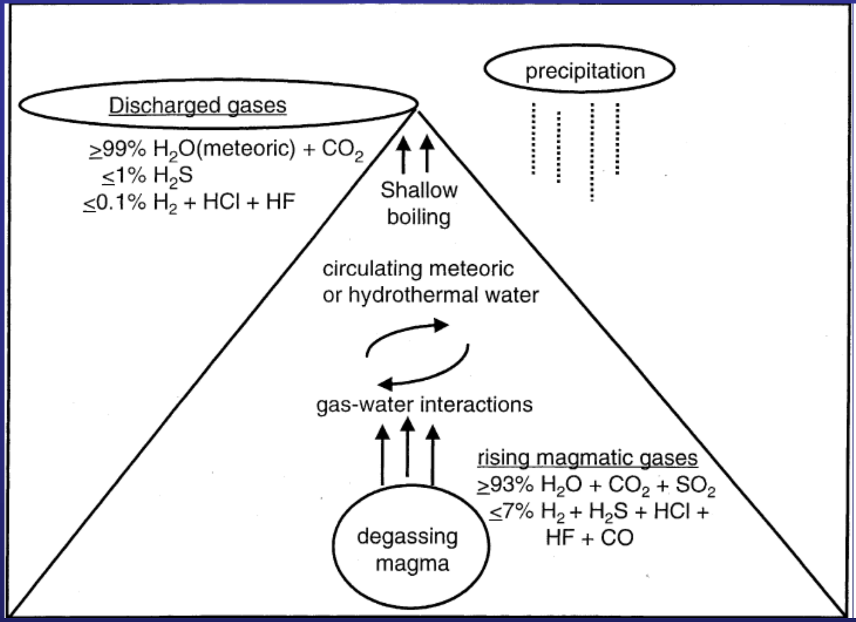


El Tatio Basin, Chile

Munoz-Saez et al, JVGR 2018

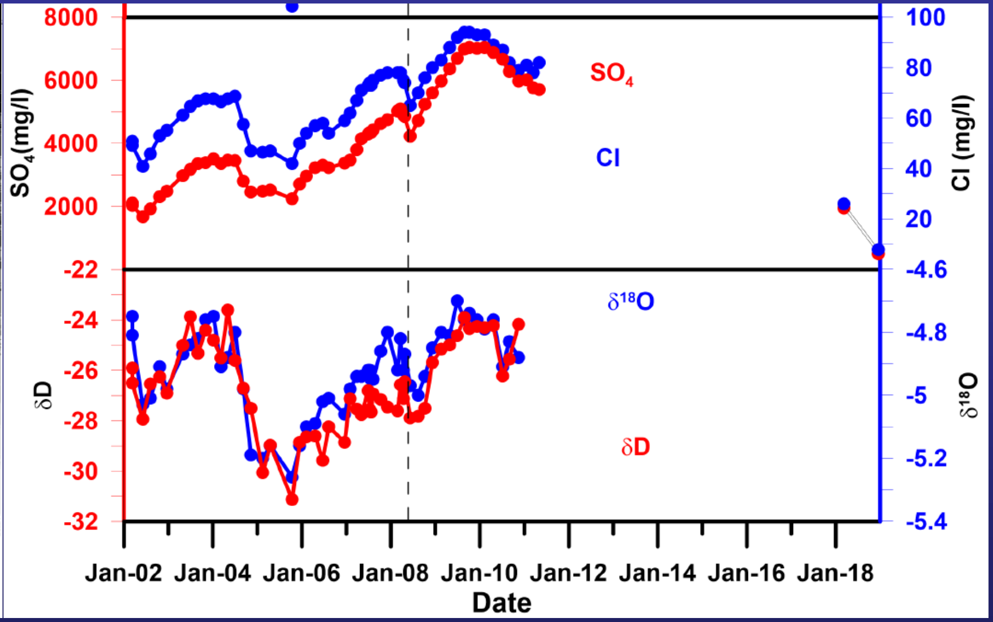
- Use thermodynamic databases to calculate saturation indices for a selected set of minerals over a range of temperatures
- Input includes water chemistry, mineral assemblage and estimates of P_{CO2}
- Available codes - Geochemist's Workbench (commercial), PHREEQC (USGS), **iGeoT (LBNL)**

Scrubbing of magmatic gases



Symonds et al., JVGR 2001

Keller Well, Kilauea

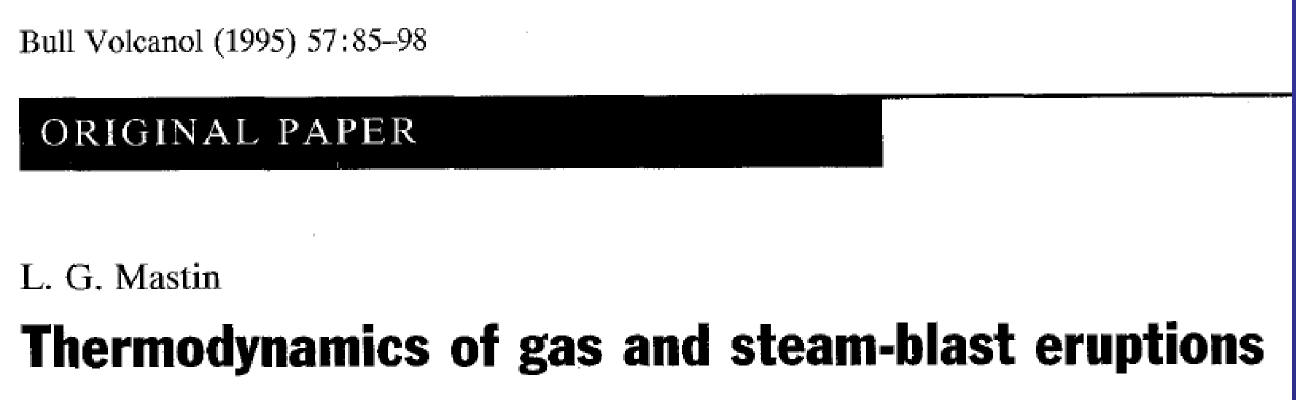


Hurwitz et al., USGS 2019

- Scrubbing will prevent significant SO_2 and most HCl emissions until a dry pathway to the atmosphere is established
- SO_4^{2-} and Cl^- in groundwater increased as a result of scrubbing until the opening of the 2008 vent

Conversion of thermal energy into kinetic and mechanical energy

- Hydrothermal explosions - phreatic eruptions
- Geyser eruptions

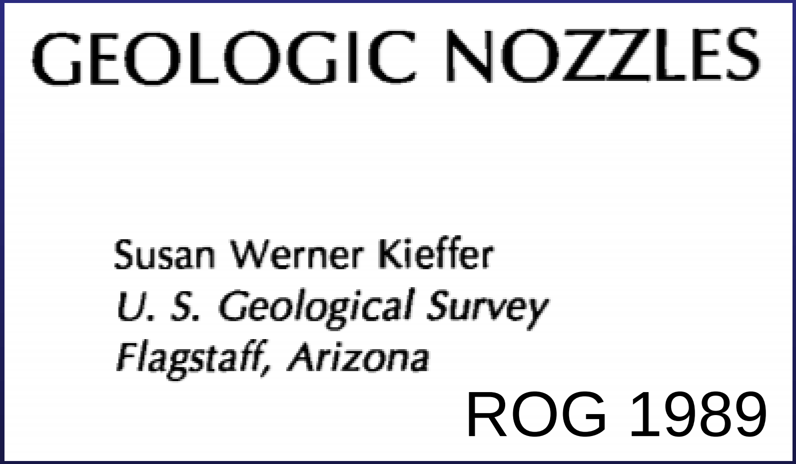


Bull Volcanol (1995) 57:85–98

ORIGINAL PAPER

L. G. Mastin

Thermodynamics of gas and steam-blast eruptions



GEOLOGIC NOZZLES

Susan Werner Kieffer
U. S. Geological Survey
Flagstaff, Arizona

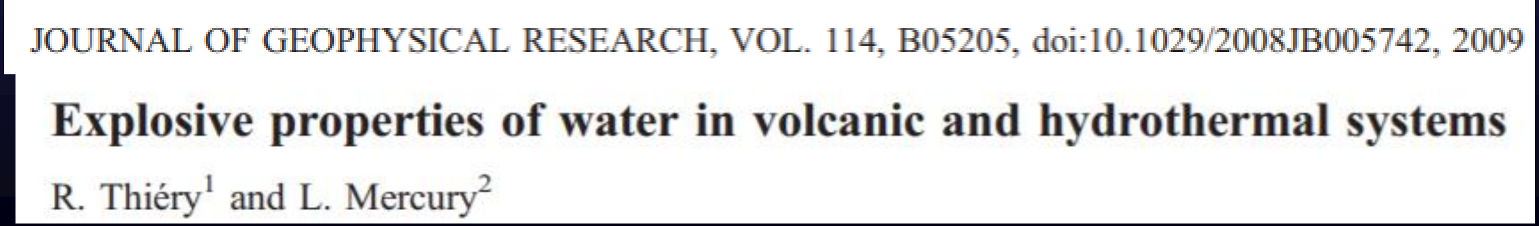
ROG 1989

Thermodynamics and Mass Transport in Multicomponent, Multiphase H_2O Systems of Planetary Interest

Xinli Lu and Susan W. Kieffer

Department of Geology, University of Illinois, Urbana, Illinois 61801;
email: xinlilu@uiuc.edu, skieffer@uiuc.edu

AREPS 2009



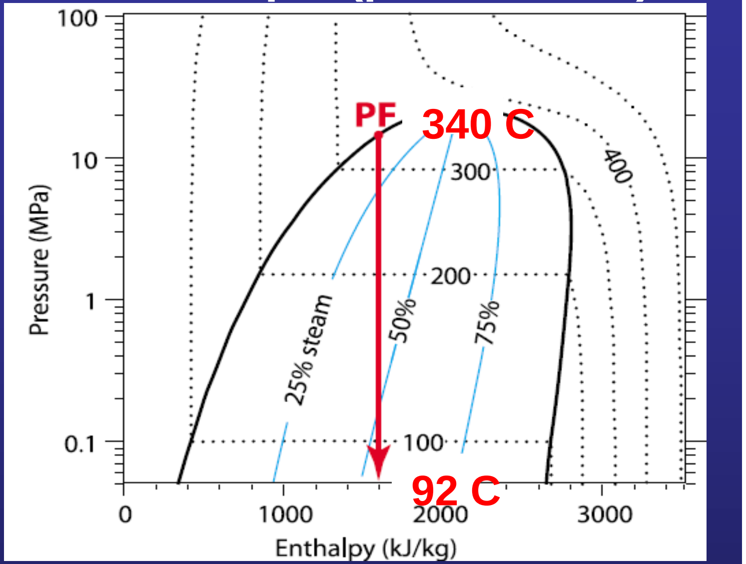
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, B05205, doi:10.1029/2008JB005742, 2009

Explosive properties of water in volcanic and hydrothermal systems

R. Thiéry[1] and L. Mercury[2]

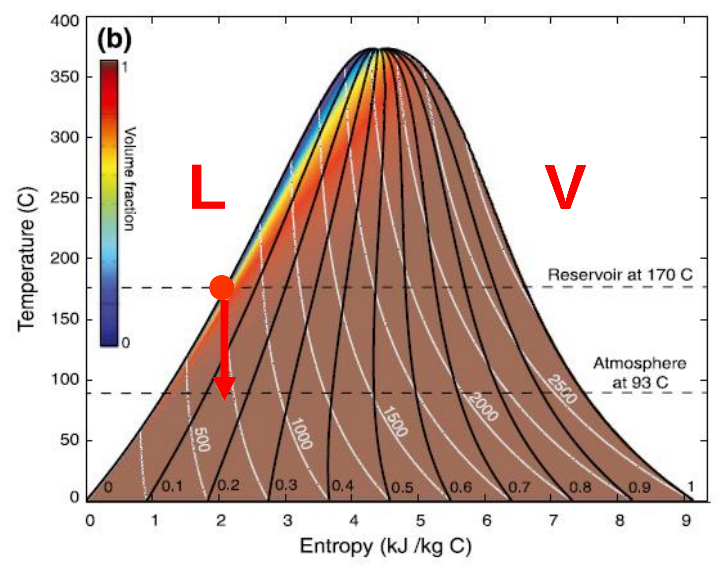
Adiabatic fluid decompression

Isenthalpic (porous flow)



Hurwitz et al. JGR 2012

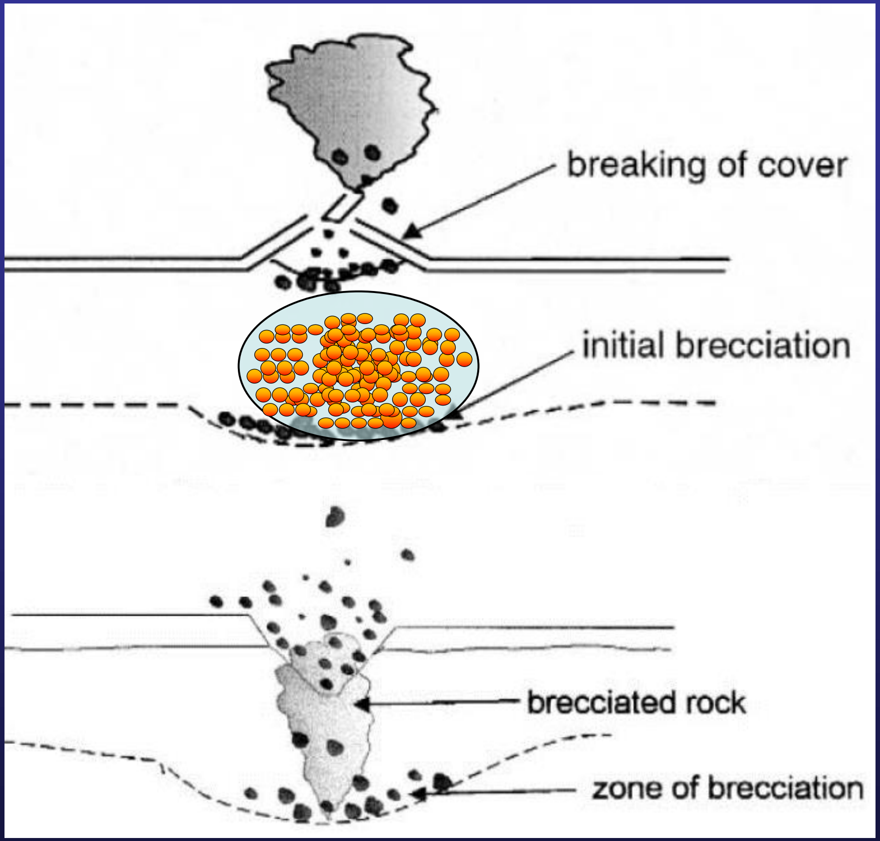
Isentropic (geyser)



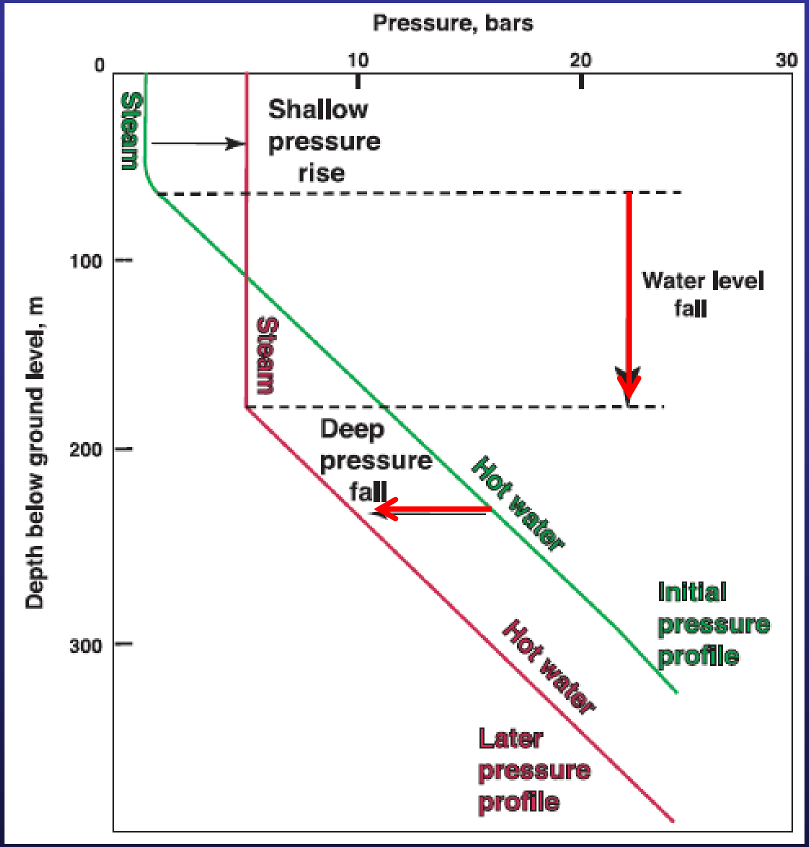
Karlstrom et al. JGR 2013

- **Isenthalpic** - all acceleration is converted to heat by internal shearing and friction – assumed for flow in porous media but not for flow in conduits (geysers)
- **Isentropic** - maximum energy available for expansion and acceleration. Valid for geysers and eruptions.

Hydrothermal explosions – phreatic eruptions



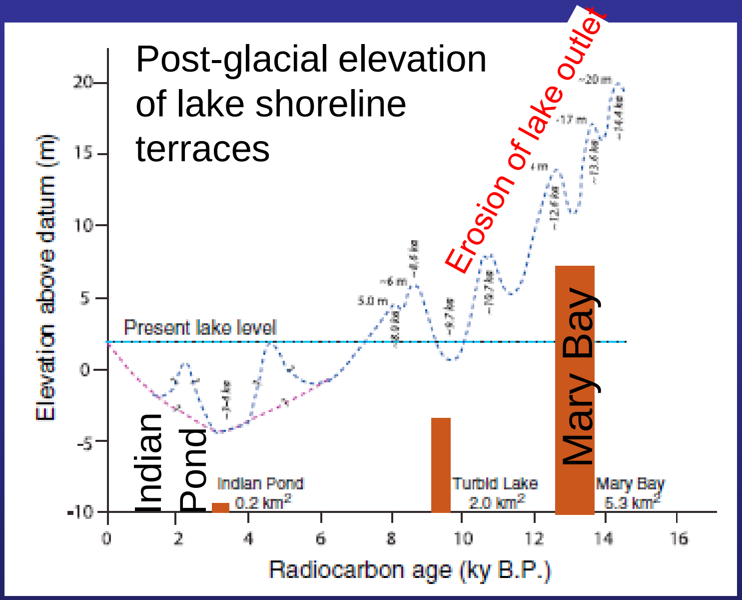
Browne & Lowless, 2001



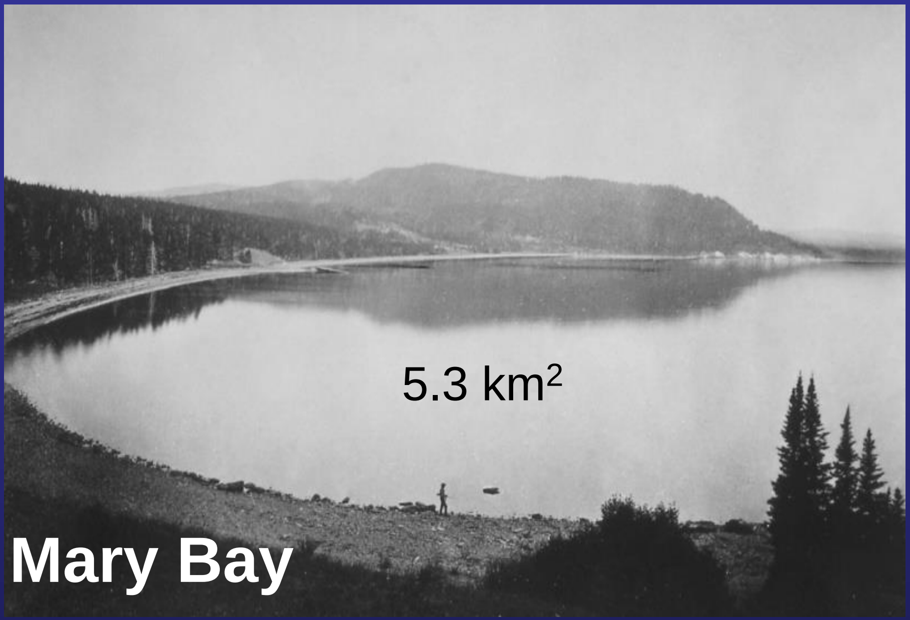
Bargar & Fournier, 1988

Decompression and vertical shift of boiling-curve – **flash to steam**

Hydrothermal explosions following deglaciation in Yellowstone

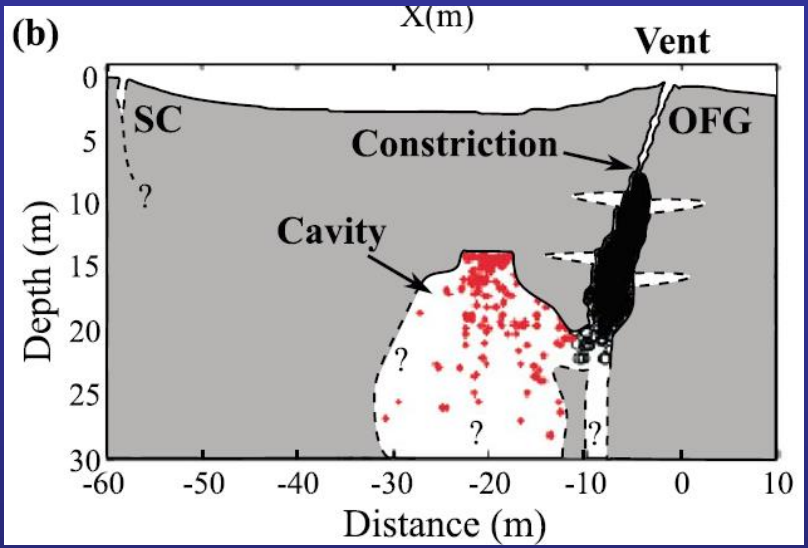


Pearce et al. USGS OFR 2004

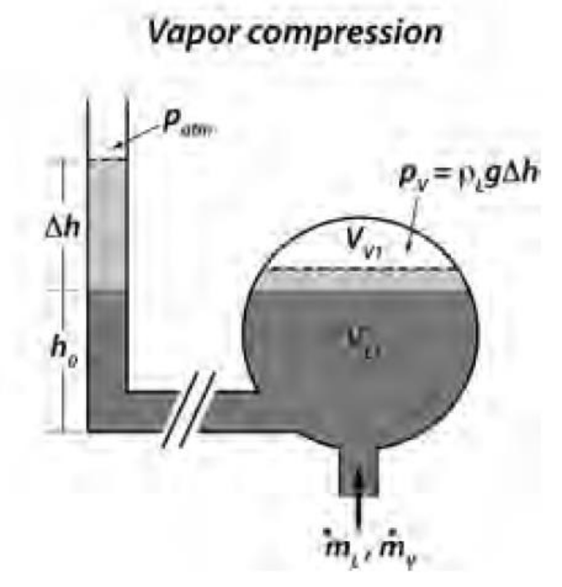


- Most of Yellowstone was covered by an ice cap <1,200 m thick
- Following the retreat of the last ice cap, pressure in the system decreased substantially, leading to extensive boiling
- Ejecta (mostly breccia) was found 3-4 km from the largest craters

Geyser eruptions and reservoirs



Vandemeulebrouck et al GRL 2013



Vandemeulebrouck et al JGR 2014

- Lateral shallow subsurface reservoirs accumulate thermal energy that is episodically discharged
- Seismic sources are produced by bubble cavitation in subsurface lateral reservoirs and the conduit

Hurwitz & Manga AREPS 2017

Steamboat geyser, Yellowstone NP

Insights gleaned from geyser studies could be used to improve the interpretation of signals recorded at volcanoes (Kieffer, 1984)

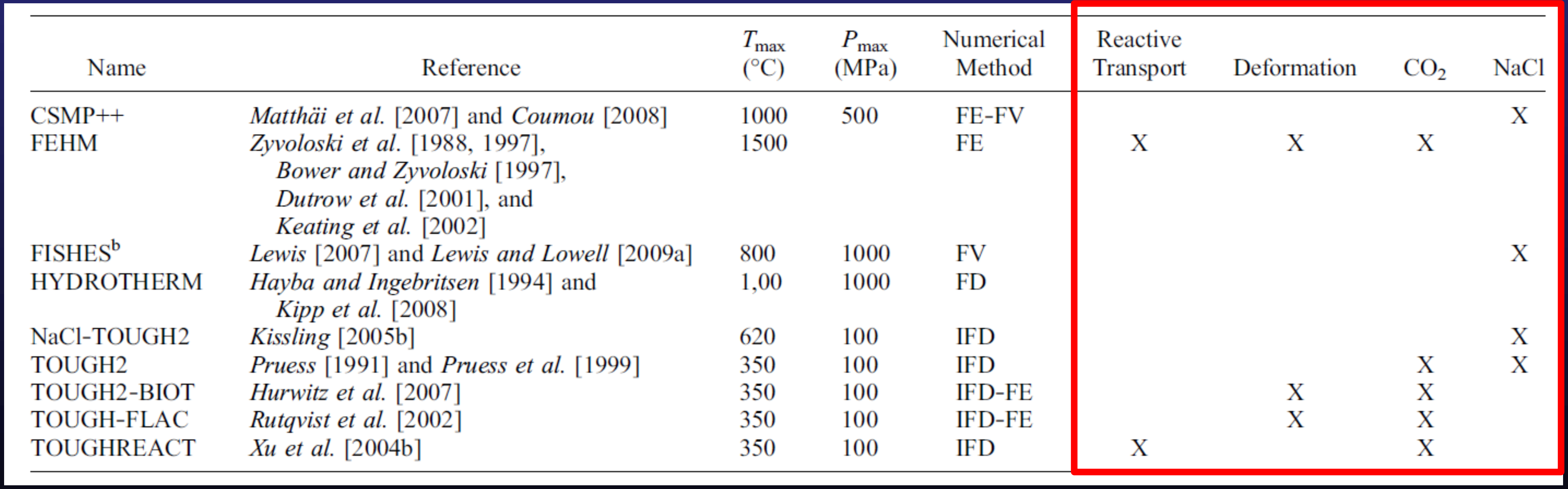
Summary – heat and volatile transport from magma to the surface

- **Hydrothermal rock alteration** - a sink or source for elements and volatiles
- **Acid-sulfate alteration** decreases the shear strength of rocks **Scrubbing** remove SO_2 and most HCl from gas emissions
- **Hydrothermal explosions and geyser eruptions** are manifestations of thermal energy conversion of into kinetic and mechanical energy
- **Mass unloading from Earth's surface** (deglaciation) can cause liquid water flashing to steam
- Subsurface **geyser reservoirs** offset from the conduit accumulate thermal energy that is episodically discharged

Numerical modeling of volcano hydrothermal systems

Numerical modeling of volcano hydrothermal systems

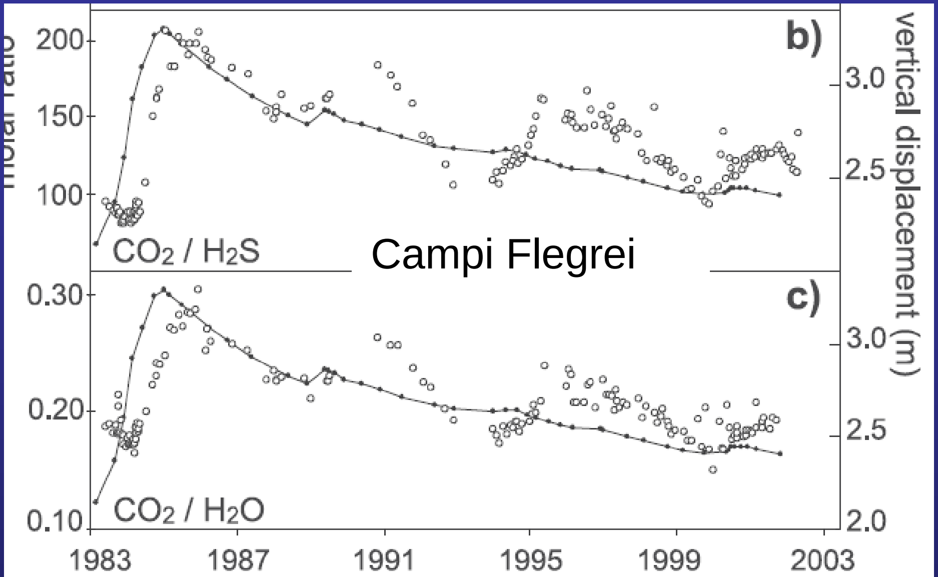
- Numerical simulators use mathematical formulations of Darcy’s Law for multiphase groundwater flow in porous media
- The simulators have different capabilities and different numerical schemes
- Many unconstrained variables – **non-unique results**



Name	Reference	T_{max} (°C)	P_{max} (MPa)	Numerical Method	Reactive Transport	Deformation	CO_2	NaCl
CSMP++	*Matthäi et al.* [2007] and *Coumou* [2008]	1000	500	FE-FV				X
FEHM	*Zyvoloski et al.* [1988, 1997], *Bower and Zyvoloski* [1997], *Dutrow et al.* [2001], and *Keating et al.* [2002]	1500		FE	X	X	X	
FISHES^b	*Lewis* [2007] and *Lewis and Lowell* [2009a]	800	1000	FV				X
HYDROTHERM	*Hayba and Ingebritsen* [1994] and *Kipp et al.* [2008]	1,00	1000	FD				
NaCl-TOUGH2	*Kissling* [2005b]	620	100	IFD				X
TOUGH2	*Pruess* [1991] and *Pruess et al.* [1999]	350	100	IFD			X	X
TOUGH2-BIOT	*Hurwitz et al.* [2007]	350	100	IFD-FE		X	X	
TOUGH-FLAC	*Rutqvist et al.* [2002]	350	100	IFD-FE		X	X	
TOUGHREACT	*Xu et al.* [2004b]	350	100	IFD	X		X	

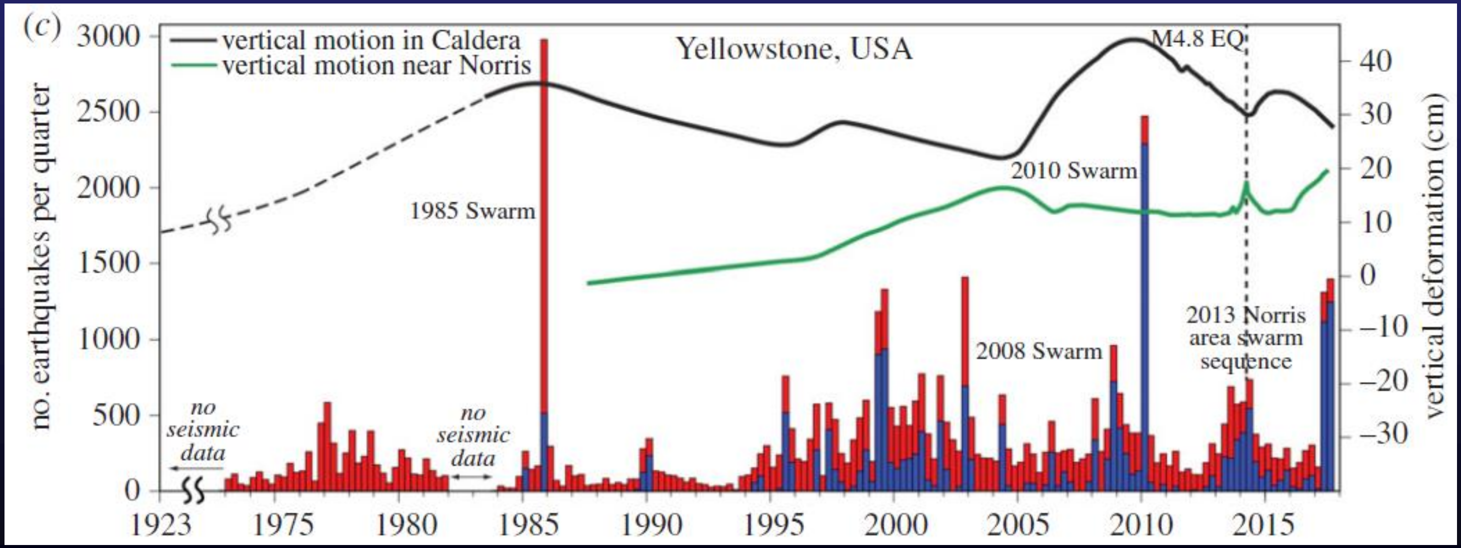
Ingebritsen et al. RoG 2010

Deformation of large calderas



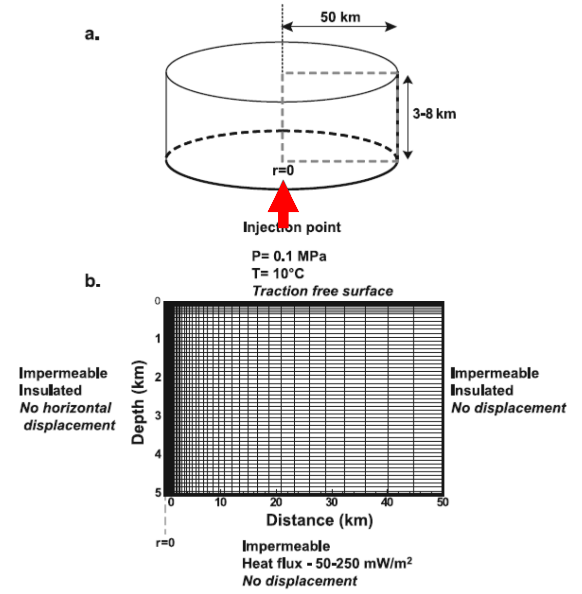
Chiodini et al. GRL 2003

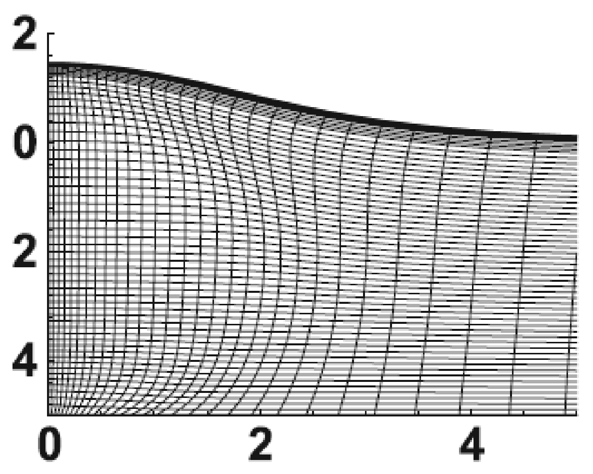
- What drives deformation?
- How are subsidence and episodic deformation explained?
- Are pressures transients within the hydrothermal system sufficient for deforming rocks?



Jamie Farrell in Pritchard et al. 2019

Simulating hydrothermal deformations of calderas

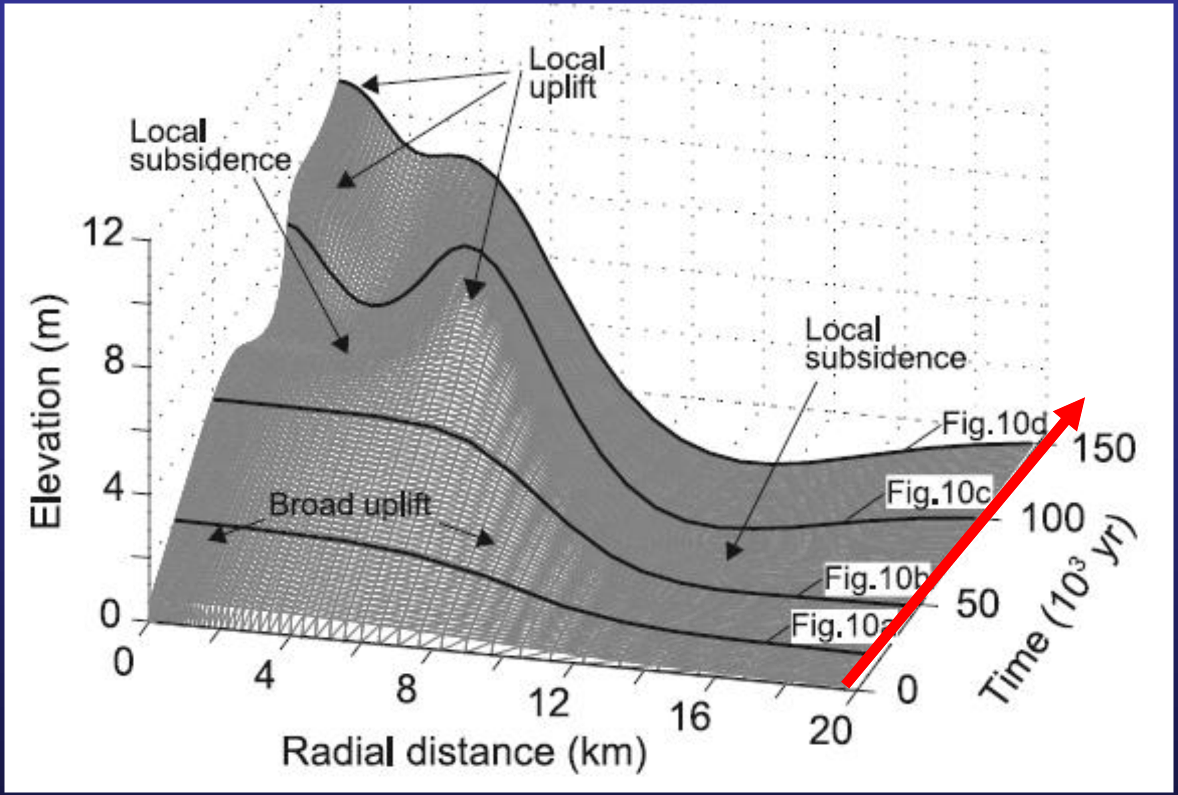




- Coupling of **TOUGH2** (multiphase groundwater flow) and **BIOT2** (deformation in a elastic porous medium)
- high-temperature water and CO_2 (350 °C) are injected at variable rates
- **Variables** - permeability and its anisotropy, the depth and rate of hydrothermal injection, shear modulus
- A range of deformation patterns and rates of vertical displacements were simulated

Hurwitz et al, JGR 2007

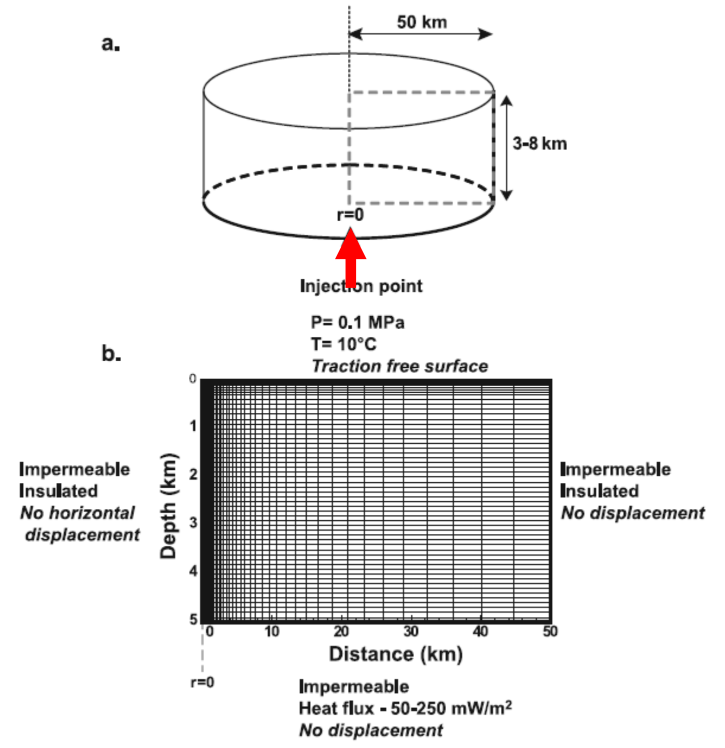
Simulating hydrothermal deformations of calderas

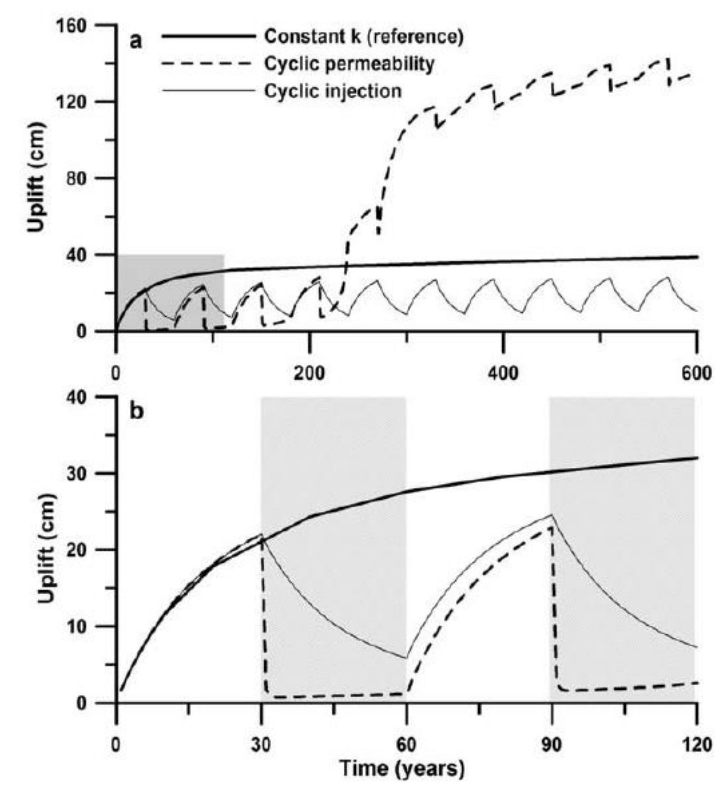


Multicomponent (H_2O–CO_2) fluids generate more complex, temporally and spatially varying patterns of deformation

Hutnak et al., JGR 2009

Simulating hydrothermal deformations of calderas

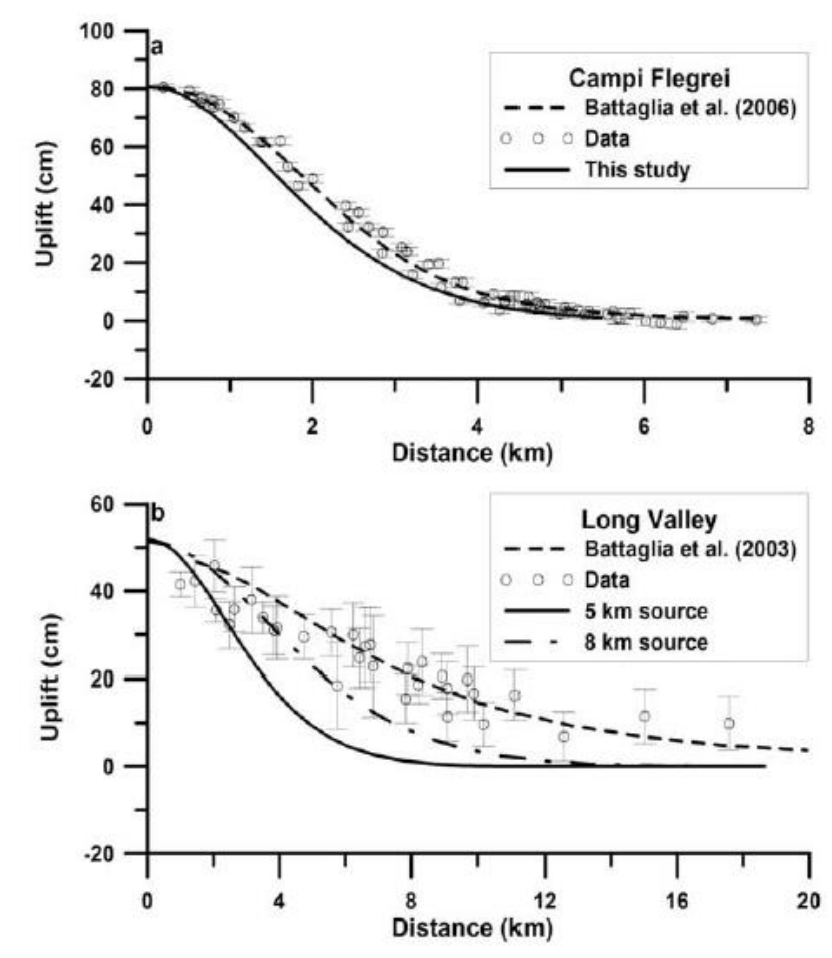




- **Cyclic deformation patterns** result from variable fluid injection rates at the base and from transient (cyclic) permeability
- Subsidence was simulated by terminating fluid injection and by increasing the permeability after uplift occurred

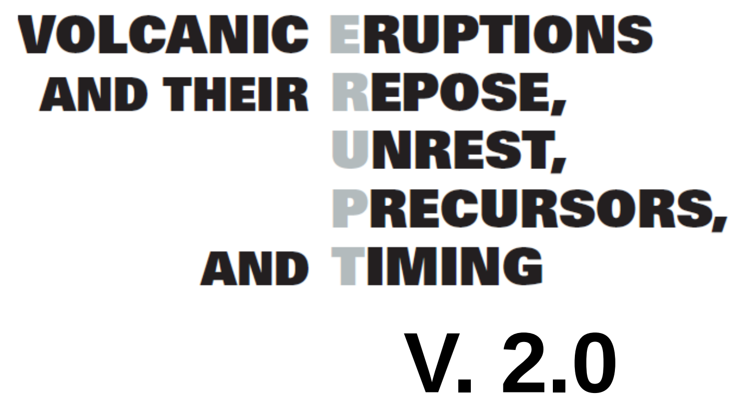
Hurwitz et al, JGR 2007

Can caldera deformation be attributed to hydrothermal dynamics?



Some of the simulated uplift rates are similar to measured rates in large calderas

Hurwitz et al, JGR 2007


VOLCANIC ERUPTIONS
AND THEIR REPOSE,
UNREST,
PRECURSORS,
AND TIMING
V. 2.0

1. Forecast the onset, size, duration, and hazard of eruptions by integrating observations with quantitative models of magma** and hydrothermal **dynamics.

Drill, drill, drill…

Lab experiments…


PROBING MAGMA RESERVOIRS TO IMPROVE VOLCANO FORECASTS

By Jacob B. Lowenstern, Thomas W. Sisson, and Shaul Hurwitz

Challenges and open questions

- Can we distinguish between magmatic and hydrothermal drivers of deformation?
- How do we interpret broadband seismic signals with multiple spectral peaks?
- Can we map the 3-D distribution of acid-sulfate alteration and liquid saturation distribution in deep stratovolcanoes?
- Can we identify precursory signals to phreatic eruptions?
- Are seismic swarms in the upper crust associated with pulses of heat and mass transport from depth?
- What are the rates of water-gas-rock reactions? How do these rates control permeability and heat and mass transport to the surface?